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STAVE PIPE—ITS ECONOMIC DESIGN AND THE ECONOMY OF ITS USE.

BY ARTHUR L. ADAMS, M. Am. Soc. C. E.

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WITH DISCUSSION.

This subject, in one or more of its aspects, has been briefly dwelt upon at various times by engineers when describing the construction of hydraulic works involving the use of pressure pipe of this type, but a full discussion of the various practical and economic problems involved in stave pipe design and the determination of its real place among standard types of pressure pipe have yet to appear.

The great dissimilarity in practice indicates either a very general unfamiliarity with the principles involved, or much difference of opinion regarding their practical application. That there is need for a better understanding of these principles, and of the correct limitations of the pipe's successful and economic usefulness, is apparent from the not infrequent partial disasters that have attended its attempted construction. That it has to-day a place among standard types of construction is apparent from the remarkable degree of favor accorded it by everyone who has used it intelligently. The author firmly believes that the use of this pipe, now chiefly confined to the West, is destined

to receive greatly extended recognition among engineers everywhere. These considerations seem sufficient to warrant this presentation, which it is hoped may serve as a starting point for the evolution of clearer and more generally accepted ideas relative, not alone to the details of stave pipe design, but to the broader question of the comparative economies of different classes of pressure pipes, a question which recent important experiments and accumulating experience have done much to reopen to argument.

In treating the subject, the author proposes to discuss the essential considerations in stave pipe design, and some of the practical and theoretical limitations imposed. Supplemental thereto a study will be made of several existing pipe lines, with reference to the details and factors used and the attendant results, and, finally, having outlined a simple and rational method for making a safe and economic design, a comparison will be made between the leading types of large pressure pipes, with reference to their relative first cost, durability and carrying capacity, from which the author will seek to determine the rightful place of stave pipe in economic construction.

General Type Considered.—At first stave pipe was principally used for penstocks in the development of water power, and was built in tapered sections which were put together after the manner of stove pipe. Apparently the first instance of its use as a continuous tube was the 6-ft. penstock constructed at Manchester, N. H., in 1874, by J. T. Fanning,* M. Am. Soc. C. E., and which is still doing service. Round bands were suggested by certain letters patent as early as 1880, and were first put into extensive use at Denver, Colo., in 1883. The particular type referred to in this paper is that which has been thus evolved, *i. e.*, a pipe which is built continuously in the trench, of staves of variable length, having radial edges and concentric faces, and which are held together by metal bands usually circular in section and spaced in accordance with the strains imposed.

Essential Considerations.—In a former contribution by the author† the following appears:

"In the design of a wood-stave pipe, the following essential points require consideration: The staves must be thin enough to secure complete saturation and to deflect readily to the degree of curvature employed, and they must be thick enough to prevent undesirable

* *Transactions*, Am. Soc. C. E., Vol. vi, p. 69.

† *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 15.

percolation through them. The bands must be of such size that, when spaced to secure the desired factor of safety against rupture, there will at the same time be no sensible flexure in the staves and no destructive crushing of the fiber beneath the bands. While fulfilling these conditions, the proportion between the thickness of the staves and the strength and spacing of the bands must be such that the swelling of the wood will not produce injurious strains upon what might otherwise be a properly proportioned band."

These are the primary considerations, generally stated, which should govern all design, and the author believes it will be profitable to consider them more in detail, to point out some of the limitations of each, the effect of certain practical considerations, and to reduce the whole to a form easy of application. To do this intelligently a clear conception of the nature and source of the probable strains set up in the construction and operation of the pipe should first be secured.

Sources of Strains.—The tensile strains resisted by the bands are from three sources:

(1) The initial strain, caused by cinching during construction.

(2) The pressure of the water within the pipe.

(3) The swelling of the staves.

The strains resisted by the staves are from the following sources:

(1) The compressive strain of the bands.

(2) The compressive strain upon the edges of adjoining staves.

(3) The pressure of the water producing flexure of the staves between adjacent bands.

The fact that most of these strains, in their amount and importance, are more or less inter-dependent makes any separate determination of the values of each impossible without coincidently determining the nature of their mutual relation under some variety of conditions.

Cinching Strain.—It is evident that to secure a pipe that shall be tight, or practically so, when first filled, the initial cinching strain must be sufficient in extent to produce:

(1) A degree of compression per square inch between the staves in excess of the water pressure.

(2) A uniform contact between the band and all the staves; and, if the band be of a curved section, a sufficient indentation of the wood to afford the band a bearing contact sufficient in area to resist, without further immediate indentation, the water pressure incident to the filling of the pipe.

If these conditions are not complied with, it is evident that leakage must ensue until the necessary compression between the staves and the requisite area of contact between the bands and the staves are supplied by the swelling of the staves. Whether this will be accomplished or not will depend chiefly upon the degree of seasoning of the staves. That the question of seasoning, in securing tight pipe, so long as the staves are uniform, is relatively unimportant, with proper cinching, seems to follow logically, though the practical difficulties incident to the handling and shipping of the heavier green timber, and the prevention of unequal shrinkage before getting the staves into the pipe, usually make the at least partially seasoned timber the cheaper. It is apparent that back-cinching, to a degree producing greater compressive strain than is essential to the foregoing requirements, is to that extent a needless addition to the cost of erection and to the band strain.

Owing to the friction between the band and the staves, and the compressive resistance of the wood, it is not found possible in practice to secure the necessary area of contact, under a band of curved section, by screwing up the nut at the end of the band, without inducing an objectionably high strain. To accomplish the result in a better way, the band is usually pounded vigorously at all points, simultaneously with the use of the wrench. Such a practice is highly commendable, and is, indeed, usually essential, as it tends to secure the proper degree of indentation with the least residual tensile strain in the band consistent with securing the requisite compression between the staves.

Just what this cinching strain usually amounts to in practice depends upon the character of and manner of doing the work, and is, probably, as variable as individual judgment. So far as it influences the success of the work, it is believed that the foregoing sufficiently elucidates the principles involved. In its effect upon the final working strain in the band, it will be shown later that a considerable variation in practice within reasonable limits will not seriously affect the final stresses, though, doubtless, much affecting the temporary strains resulting on first filling.

Water Pressure Strain.—The strains induced in the bands by the pressure of the water within the pipe are susceptible of positive determination, and the methods of their solution are too well known to require any explanation herein.

Strains from Swelling Staves.—The additional strain caused by the swelling of the staves is less easily determined, and exists only within certain limitations of the first afore-mentioned source of strain.

With swelling timber, as with a steel spring, it may be assumed that its expanding power, at a given stage of compression, well within what may be called its elastic limit, is measured by the load necessary to produce that compression under like conditions. Hence its ultimate swelling power, at a given degree of compression, is the measure of its ultimate resisting power. It is also influenced by the hardness, direction of grain and such other conditions as affect the compressive strength of timber within its elastic limit when resisting forces applied across the grain.

If, then, the staves in a pipe be compressed laterally by the bands beyond the elastic limit of the saturated wood, there can be no swelling of the staves, and, consequently, no increased strain in the bands from this source. On the contrary, a farther compression of the fiber will result until an equilibrium is established between the compressive strain and the sustaining power of the wood; and if the sustaining power is below that requisite to resist the pressure of the water, leakage will, of course, result. If, on the other hand, the compression is less than the corresponding swelling power of the wood at the degree of seasoning and compression used, the timber will, by swelling when wet, develop an expanding power in some degree commensurate with the ratio of the volume of the uncompressed saturated stave to the same when compressed to the degree used, which expansion, of course, induces a correspondingly increased strain in the bands.

Thus there results the rather remarkable condition that if the bands, in resisting the water pressure, tax the staves beyond the limit of their permanent compressive strength, they, by yielding, release the excess of pressure, and leakage results, and if less is required of them than the most they are capable of giving, they force the band to take all the additional strain they are capable of exerting.

The amount of additional band strain thus induced is, doubtless, nearly proportional to the area of contact between the staves in the straight seams. The avoidance of unnecessary thickness of staves, too long band spacing and the providing of such an area of contact between band and staves as shall give a necessary working compressive strain on the wood, not in excess of its permanent resisting strength,

and only sufficiently below it to make certain of its not being exceeded by the water pressure, ought, therefore, to commend themselves as prime essentials in avoiding unnecessary and perhaps injurious band strains.

The special advantage of a band of curved section, as contrasted with a flat band, now becomes apparent, since by the former a permanent compressive strain on the wood is provided sufficient to produce a decided indentation. The swelling of the staves, if any, and the accompanying increased compressive strains beneath the band are, therefore, followed by a farther yielding of the wood; and as the band strain increases, the area of contact with the band is increased by the farther indentation of the stave. With flat bands the unit compressive strain beneath them would almost invariably be so low that no indentation of the stave would result, and swelling strains to the full exerting power of the wood would be added to the band strains arising from other sources.

Temporary and Permanent Strains.—From the foregoing it is apparent that the strains resulting on first filling a pipe, or temporary strains, the necessary strains for permanently maintaining a tight pipe under pressure, and the permanent strains finally obtaining in the pipe, are three separate and usually very different quantities.

The permanent strains in a band are evidently the sum of those induced by final cinching, by water pressure and by the transverse swelling of the staves, subject only to the limitations imposed by the sustaining and swelling power of the wood when saturated.

The band strain necessary to maintain a tight pipe has already been shown to be that requisite to resist the water pressure and to maintain any excess of pressure between the staves needed to prevent seam leaks.

The temporary strain induced on first filling is the sum of the final cinching strain, the water pressure strain, and that arising from a swelling of the staves, subject only to the limitation of the immediate compressive resistance of the wood under the band while still dry, a limit scarcely reached in any proper construction.

Strains Resisted by Staves.—In discussing the causes and effects of band strains, the character of the strains resisted by the staves have been made sufficiently plain. Their further influence upon proper design will be considered later.

Equations Deduced.—In the following equations for the various strains previously considered, the symbols used are as follows:

R = the internal radius of the pipe,
r = the radius of the band section,
t = the thickness of the stave, in inches,
f = the spacing of the bands between centers, in inches,
S = the tensile strain in the band, in pounds,
s = the safe tensile strain in the band, in pounds,
E = the permanent sustaining power of the staves, in pounds per lineal inch of band,
E' = the temporary sustaining power of the staves, in pounds per lineal inch of band,
E'' = the permanent swelling force of the wood, in pounds per square inch,
E''' = the temporary swelling power of the wood, in pounds per square inch,
P = the water pressure, in pounds per square inch,
e = the safe bearing power of the wood, in pounds per lineal inch of band,
X = the additional strain induced by band cinching, in pounds.

The least band strain induced by water pressure $= P\,R\,f$.

The permanent band strain induced by swelling of staves $= f\,t\,E''$.

The least permanent strain in the bands of a tight pipe $= (X + P\,R\,f + f\,t\,E'') < R\,E$. Assuming $X = \frac{3}{2}\,t\,f\,P$ and substituting, we have as the least permanent value of S for a tight pipe when $P < E''$

$$S = \left(P f\,(R + \tfrac{3}{2}\,t) + E''\,t\,f\right) < (R + t)\,E \ldots\ldots\ldots (1)$$

If $P > E''$, this becomes

$$S = \left((R + \tfrac{3}{2}\,t)\,P\,f\right) < (R + t)\,E \ldots\ldots\ldots\ldots\ldots (2)$$

which is the equation generally used for computing band strains for all pressures.

The least temporary band strain induced on first filling a tight pipe $= (X + P\,R\,f + E'''\,t\,f) < (R + t)\,E'$. Assuming, as before, $X = \frac{3}{2}\,t\,f\,P$ and substituting, we have as the temporary value of S when $P < E'''$

$$S = \left(P f\,(R + \tfrac{3}{2}\,t) + E'''\,t\,f\right) < (R + t)\,E' \ldots\ldots (3)$$

If $P > E'''$, the equation becomes the same as (2).

From the foregoing the following equations, convenient for application, are deduced:

When $P < E''$:

$$f = \frac{s}{(R + \frac{3}{2}t)\ P + E''\ t}, \text{ when } s < (R + t)\ e \ldots\ldots\ldots (A)$$

$$f = \frac{(R + t)\ e}{(R + \frac{3}{2}t)\ P + E''\ t}, \text{ when } s > (R + t)\ e \ldots\ldots\ldots (B)$$

When $P > E''$

$$f = \frac{s}{(R + \frac{3}{2}t)\ P}, \text{ when } s < (R + t)\ e \ldots\ldots\ldots\ldots\ldots (C)$$

$$f = \frac{(R + t)\ e}{(R + \frac{3}{2}t)\ P} \text{ when } s > (R + t)\ e \ldots\ldots\ldots\ldots\ldots (D)$$

Inasmuch as stave pipe has never been used under heads where the value of P is greater than E'', and since, as will subsequently be seen, it has not as great economic value under such heavy pressures as under lighter pressures, formulas (C) and (D) have no great practical value.

Sustaining and Swelling Power of Staves.—In order to make use of the formulas, it is essential that proper values be determined for E, E', E'', E''' and e.

Since the sustaining power of wood depends upon the degree of its permissible compression within the limit of its ultimate crushing, it is necessary to assume some fixed amount of stave indentation as a basis for determining the probable values of E and E'. Now, in the actual process of pipe construction, it has been frequently observed that an indentation equal to one-eighth of the radius of a round band, of such sizes as other considerations render suitable for use, may be produced in the stave without breaking the fiber, while any considerable increase beyond this point has a destructive effect. This degree of indentation gives a bearing surface equal to half the diameter of the band, which may, therefore, be assumed as the greatest that can be safely obtained.

In considering contact between cylindrical bodies and the flat surfaces of saturated timber, the ordinary experimental data relating to flat surfaces having uniform contact with seasoned timber are scarcely

applicable. The scarcity of experiments influencing the correct determination of these values is to be regretted, and it is hoped will yet be supplied. So far as the author is aware, the only experiments available are those made by D. C. Henny,* M. Am. Soc. C. E. A further study of these experiments forecasts some interesting conclusions regarding these values, and additional light is derived from a study of the strains prevailing in some existing pipe lines, as will be shown later. The experiments mentioned were made to determine the swelling power of Oregon "yellow fir." For convenience, the results are here given:

TABLE No. 1.

Date of immersion.	Date of observation.	Observed strain in bands, in pounds.	Corresponding strain, per square inch between staves.	Corresponding strain on staves under band, per lineal inch of band.	Corresponding strain on staves under band, per square inch of contact.	Remarks.
			Section 1, No. 1.			
Feb. 27	Feb. 27	4 750	288	456	1 830	Initial strain before submerging.
	Mch. 1	3 400	206	328	1 310	
	" 4	2 950	179	284	1 140	
	" 7	2 750	167	265	1 060	
	" 9	2 525	153	243	970	
	" 12	2 525	153	243	970	
			Section 1, No. 2.			
	" 12	100	7	10	38	Band was loosened to the strain indicated.
	" 18	1 500	91	145	580	
	" 21	1 500	91	145	580	
	" 26	1 550	94	150	600	
			Section 1, No. 3.			
	" 26	500	30	48	190	Band again loosened to the strain indicated.
	April 1	1 000	61	97	390	
	" 4	1 050	64	101	400	
	" 8	1 100	67	106	420	
	" 11	1 200	73	116	460	
	" 15	1 225	74	118	470	
			Section 2, No. 1.			
Apr. 16	" 16	450	33	43	170	Band was first drawn to tension of 5 000 lbs. and then released to the strain indicated.
	" 17	1 400	85	135	540	
	" 20	1 900	115	183	730	
	" 24	2 000	121	192	770	
	" 27	1 975	120	190	760	
	May 1	1 900	115	183	730	
	" 4	1 900	115	183	730	
	" 7	1 800	109	173	690	
	" 10	1 700	103	164	660	
	" 13	1 600	97	154	620	
	" 17	1 600	97	154	620	

In these experiments the bands were depressed into the staves until a bearing of half their diameter was secured.

* "The Astoria City Water-Works." *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 18.

In experiment No. 1, with Section 1, it will be noted that a very heavy initial tension was put upon the band, which the staves after being immersed could no longer withstand. The resulting compressive strain resisted by the staves under the bands accordingly fell from 456 lbs. per lineal inch of band to 243 lbs., or 970 lbs. per square inch of contact, at which point it became stationary, although, the staves being at this stage probably incompletely saturated, a longer immersion might have resulted in producing a slightly lower permanent resistance. The result is strongly indicative that this pressure of 970 lbs. per square inch of contact is the utmost that in practice can be permanently resisted by the staves, while the subsequent experiments show that hard cinching and a full band-bearing as here used are necessary to secure nearly so high a resistance. As will be noticed later, the correctness of this general deduction is practically substantiated by a study of some existing structures.

The resulting compression between the staves in this experiment is seen to be 153 lbs. per square inch, a figure from which no conclusion can be drawn other than that the diminution in the band strain must have been the result of yielding under the band rather than between the staves.

Experiments Nos. 2 and 3, with the same section, in which the band tension was successively released by means of the wrench, are evidently well calculated to determine the approximate swelling force exerted laterally by the staves. The staves having been compressed for a period of two weeks, to a degree under the bands well beyond the limit of the wood's elasticity, it is evident that a very slight lengthening of the band by unscrewing the nut would be immediately followed by the partial or entire release of the band strain. The amount of lengthening necessary for this result would doubtless be but a small fraction of the total of, say, 3% expansion by swelling, of which the kiln-dried timber would be capable, if unresisted. The staves, not having been compressed laterally in the previous experiment to a degree in any way calculated to impair their swelling power, were then free to develop this power to the utmost within the limit of their ultimate bearing power under the bands, which the previous experiment has shown to be not less than 970 lbs. per square inch of contact. On the first release of the band strain, No. 2, the staves developed a swelling power of 94 lbs. per square inch. On the second

release, they developed a power of 74 lbs. per square inch, the power diminishing, as might be expected, as the wood gradually approached its full unrestrained proportions.

The experiment with Section 2 is a confirmation of the results derived from experiment 2, on Section 1. The pipe was but slightly cinched after the band had been brought to a proper bearing. The staves developed a swelling power of 97 lbs. per square inch, a figure almost identical with that given by the previous experiment, while the resulting compressive strain under the band, 620 lbs. per square inch, was not such, under the prevailing conditions, as to be likely to cause a degree of yield which would vitiate the result.

So far as they go, these experiments demonstrate: (1) That with a proper degree of compression, an ultimate permanent pressure of between 900 and 1 000 lbs. per square inch of contact with the band may be resisted by the staves. This result may probably be conservatively assumed to obtain in the use of all bands of prevailing sizes, and of staves without regard to the character of the grain. (2) That the ultimate swelling power of the wood may be taken at from 90 lbs. to 100 lbs. per square inch of stave contact in straight seams, a result which may be effected by the spacing of the bands, since a slight flexure in the stave would tend to release the strain instead of transmitting it to the bands. (3) That for water pressures exceeding, say, 94 lbs. per square inch, and probably considerably less, hard cinching, rather than the swelling of the wood, must be relied upon to maintain a tight pipe. (4) That the yielding quality of the wood renders hard cinching not seriously objectionable in its effect upon final band strains with the usual factors of safety in the band and when working reasonably close to the limit of ultimate compressive resistance of the stave.

As it has been observed in practice that the difference in the compressive strength of Douglas fir and redwood is not very great, when both are saturated, for present purposes no distinction will be made between them.

One of the most important points to be determined from the foregoing is the maximum value for e which can be used with entire safety in designing a pressure pipe. It will be shown later that pressures as high as 1 100 lbs. per square inch have been successfully used under favorable conditions, but the logical conclusions drawn from the pre-

vious discussion, as well as some results from actual experience given later, strongly indicate that such an assumption is insufficiently conservative for entirely safe construction. With thorough compression of the bands into the staves, well-seasoned lumber, skilled construction and entire immunity from water-hammer, it would seem that this value should not be taken much, if any, above 800 lbs. per square inch, while if subject to any considerable fluctuations of pressure, or to doubtful constructive skill, a much lower figure should be used.

In view of the foregoing, the following values are assigned for use in the formulas previously given:

E = 240 lbs. for $\frac{1}{2}$-in. bands, when the fiber is fully compressed (960 lbs. per square inch).

E' = say 500 lbs., in the absence of any experiment.

E'' = 95 lbs. for 12-in. band spacing. Assumed at 100 lbs. for all spacings.

E''' = 120 lbs. for 12-in. spacing. Assumed at 125 lbs. for all spacings.

e = equivalent of 800 lbs. per square inch of band contact or less.

Determination of the Proper Size and Form of Band.—Before making use of any formula for the determination of proper band spacings, it is necessary to determine the size and form of section of the band that will most economically fulfill the requirements of any particular case in hand. The selection will be influenced by the following considerations: Bands less than $\frac{3}{8}$ in. in diameter are not suitable for use chiefly because of torsional weakness and difficulty of upsetting. An increase in the permissible value of e may be obtained without increase of metal section of band by using an oval form, which can be obtained at only a slight increase of cost above the rounds of similar weight. The price per pound for the bands is less for the heavier than the light sections. The use of upset rods or rolled threads is always economical, the latter being usually preferable because of the more perfect workmanship. The heavier the bands used, the fewer to be handled, the less the cost for both material and labor, and the better the condition of the band section for resisting corrosion, though the added stiffness, increasing the difficulty of placing, will in the larger sizes partially offset these advantages.

Referring to the formulas for band spacing, it is seen that economy in the use of the steel requires the selection of a band of such sectional

area that if possible $s < (R + t)\, e$, as otherwise it is necessary to use closer spacing—more steel—than the pressure requires, in order to secure a sufficiently low value for e.

By writing $s = (R + t)\, e$, the greatest value of s for any given band section that can be used consistently with a desired value of e, may be determined; and, by substituting for s and e their proper values corresponding to bands of various standard sizes, the limitations of the economic use of each may be ascertained, thus:

$$R + t = \frac{s}{e}.$$

TABLE No. 2.—MINIMUM SIZES OF PIPE TO WHICH SPECIFIED BANDS ARE APPLICABLE WITHOUT EXCEEDING VALUES OF 650 LBS. AND 750 LBS. FOR e, AND A FACTOR OF 4 FOR THE BANDS.

Size of band.	s (= ¼ ultimate strength.)	Band pressure per square inch.	e (Band pressure per lineal inch.)	Least external radius of pipe.	Band pressure per square inch.	e (Band pressure per lineal inch.	Least external radius of pipe.
¾ in.....	1 650 lbs.	650 lbs	122 lbs.	13.5 ins.	750 lbs.	140 lbs.	11.8 ins.
⅞ "	2 250 "	"	142 "	15.8 "	"	164 "	13.7 "
1 "	2 950 "	"	163 "	18.1 "	"	187 "	15.7 "
1⅛ "	3 725 "	"	183 "	20.4 "	"	211 "	17.65"
1¼ "	4 600 "	"	203 "	22.6 "	"	234 "	19.6 "
1½ "	6 600 "	"	244 "	27.0 "	"	281 "	23.5 "

A factor greater than 4 must therefore be used in the steel in designing pipes of smaller diameter, if bands of round section are used and the specified values of e are not exceeded. The band strains to be used are readily determined by the same formula as before indicated:

$$s = (R + t)\, e.$$

By the use of a band of oval section, a greater bearing surface is secured between the band and the stave with the same degree of indentation, thus permitting the use of less steel for given values of e, in designing pipes of small diameter. For this reason they have been already introduced and used by the Excelsior Wooden Pipe Company of San Francisco on a number of pipe lines, though not with the economy that would now attend their use, as manufacturers have not until recently been able to quote the present figures, which are but little in excess of the price for rounds. These conditions will doubtless lead to the general use of the oval section on small pipes,

TABLE No. 3.—Greatest Band Strains Consistent with Specified Values of e for Pipes of Small Diameter.

$\frac{3}{8}$-in Round Bands.

Internal diameter of pipe.	External radius of pipe	s (= Assumed working strain on band).	Factor of safety in band.	s (= Assumed working strain in band).	Factor of safety in band.
	e = 122 lbs. = 650 lbs. per square inch.			e = 140 lbs. = 750 lbs. per square inch.	
12 ins.....	7.1	866 lbs.	7.6	994 lbs.	6.1
16 "	9.2	1 122 "	5.9	1 288 "	5.1
20 "	11.2	1 366 "	4.8	1 568 "	4.2
24 "	13.5	1 650 "	4.0		

though any departures from the round sections have the disadvantage of exposing a greater relative surface to corrosive action.

The use of an oval section in the above cases would result in a saving of about 17% of the steel.

Band Spacing.—If, in accordance with the foregoing, the proper band is determined for a pipe of given diameter, formulas A, B, C or D may at once be applied to determine the proper spacing for any pressure and thickness of stave, the selection for any case being made by observing the relative values first of P and E, and then of s and $(R + t)\ e$ as indicated.

Requisite Thickness of Staves.—The staves must be thick enough to prevent percolation, to resist undue flexure with the band spacing adopted, to prevent cracking or crushing of quarter-sawed staves during the process of cinching, and to afford the rigidity necessary to support the weight of the pipe and back-filling without distortion. With these requirements met, the staves, for reasons already mentioned, should be as thin as possible.

Concerning percolation through the staves, the author has already pointed out* that in using Douglas fir under pressures in excess of about 80 ft., vertical and bastard-grained staves only should be used if the staves are $1\frac{3}{4}$ ins. in thickness. With this precaution trouble will not arise from the splitting of quarter-sawed staves, and this thickness will be found sufficient to resist percolation at any pressure under

* The Astoria City Water-Works," *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 16.

which stave pipe is likely to be used. Redwood, being of finer grain, gives no trouble from percolation.

If the size of band for a pipe of any diameter, and the band spacings are determined in accordance with the foregoing principles, staves of the thicknesses generally used will always be safe against undue flexure if a maximum spacing of 12 ins. is adopted. This is by no means an extravagant assumption, since this spacing will in most cases correspond to a very light water pressure; and if, when designing a pipe of large diameter, the band selected gives an unnecessarily large factor under light heads with this spacing, a smaller band can be substituted.

A practical consideration that has influenced very properly the thickness of staves is the desirability of running them from timbers of commercial sizes. Thus, by enabling the mill to dispose of rejected pieces, a lower price on the accepted staves is secured.

The practice of running staves from 2 ins. x 6 ins., 2 ins. x 8 ins. and 3 ins. x 8 ins. stock nearly meets the economic requirements of pipes designed in accordance with the foregoing principles, which requirements will, however, be a little better conserved if $1\frac{1}{2}$ ins x 4 ins. is used for the smallest diameters, and if the odd size $2\frac{1}{2}$ ins. x 8 ins. is used for certain sizes of pipes intermediate between those for which 2 ins. x 6 ins. and 3 ins. x 8 ins. are used.

A careful study of these and other requirements points to the following as being for general use the best balance between the various influences affecting the relation between pipe diameters and the size of stock for staves, the staves in each case being run as thick as the stock will permit.

Pipe diameters.	Stock sizes.
10 ins. to 14 ins.	$1\frac{1}{2}$ ins. x 4 ins.
16 " to 48 "	2 " x 6 "
50 " to 58 "	$2\frac{1}{2}$ " x 8 "
60 " to 72 "	3 " x 8 "

Suggested Standard Designs.—Assigning to e the conservative value of $\frac{650}{r}$, the author ventures to submit the following table of pipe diameters, with the corresponding stave thicknesses and character of bands, which, for the conditions of general use, he believes to be as closely in accord with sound theory and economic practice as the

present state of investigation and the constructive art will permit. The economy of these relative proportions is somewhat influenced by the locality of construction as affecting freight rates on the steel, but not to a serious extent. Should it be desired to use some other value of e than that designated, the needed modification can be made without difficulty.

TABLE No. 4.—Economic Proportions for Pipe Design.

Nominal diameter.	Stock sizes for staves.	Thickness of finished staves.	Economic sizes of bands.	s (Permanent band strain).	Factor of safety in band.	e (Maximum values $= \frac{650}{r}$.)
Inches.				Lbs.		Lbs.
10	1½ ins. x 4 ins.	1 1/16 ins.	5/16 x 7/8 in.	1 255	5.26	207
12	1½ " x 4 "	1 1/16 "	5/16 x 7/8 "	1 475	4.47	207
14	1½ " x 4 "	1 7/16 "	5/16 x 7/8 "	1 650	4	.....
16	2 " x 6 "	1 7/16 "	5/16 x 7/8 "	1 650	4	.....
18	2 " x 6 "	1 5/8 "	5/16 x 7/8 "	1 650	4	.....
20	2 " x 6 "	1 5/8 "	5/16 x 7/8 "	1 650	4	.....
22	2 " x 6 "	1 5/8 "	○ 3/4 in.	1 508	4.4	122
24	2 " x 6 "	1 5/8 "	○ 3/4 "	1 650	4	.....
27	2 " x 6 "	1 7/8 "	○ 3/4 "	1 650	4	.....
30	2 " x 6 "	1 7/8 "	○ 3/4 "	2 673	4.4	162
36	2 " x 6 "	1 7/8 "	○ 3/4 "	2 950	4	.....
42	2 " x 6 "	1 7/8 "	○ 3/4 "	2 950	4	.....
48	2 " x 6 "	1 1/8 "	○ 3/4 "	2 950	4	.....
54	2½ " x 8 "	2 1/8 "	○ 3/4 "	4 600	4	.....
60	3 " x 8 "	2 1/8 "	○ 3/4 "	4 600	4	.....
66	3 " x 8 "	2 3/8 "	○ 3/4 "	6 600	4	.....
72	3 " x 8 "	2 3/8 "	○ 3/4 "	6 600	4	.....

Some Existing Pipe Lines.—In seeking data concerning pipe lines already constructed, the author has encountered the customary indifference or unwillingness on the part of many engineers to divulge anything pertaining to the methods used in the design and execution of the work done under their supervision. Especially has this been the case where defects of a serious nature have developed. This is, of course, a matter for regret, since the most instructive deductions can usually be made from such experiences. Chief among the works which might well be made instructive to the profession, but which, for the above reasons is necessarily here omitted, is the 36-in. and 38-in. outfall sewer of the City of Los Angeles, Cal.

On the other hand, the author wishes to express his grateful recognition of the courtesies extended by those engineers whose appreciation of the advantage to the profession arising from a general discussion of engineering subjects by engineers has largely made possible the preparation of this paper.

TABLE No. 5.—STRAINS IN SOME EXISTING PIPE LINES.

Number.	Location of pipe.	Date of construction.	Nominal diameters, in inches.	Length, in miles.	Thickness of staves, in inches.	Kind of wood.	Character of round bands.	Ultimate strength of bands.	Maximum band spacing, in inches.	Feet pressure, for maximum spacing.	Minimum band spacing, in inches.	Feet pressure, for minimum spacing.	Band strain, from water pressure.	Band strain, from least practicable cinching.	Resulting band factor, neglecting strain from swelling staves.	Band strain, from swelling staves.	Resulting factor in band, including all strains.	Least band pressure on staves per linear inch, to maintain tight pipe.	Least band pressure on staves per square inch, to maintain tight pipe.	Total probable band pressure on staves, per linear inch of band.	Total probable band pressure on staves, per square inch of band contact.
1	Denver, Colo.	1889	90	18.00	1⅜	.....	1¼-in. upset	11 800	12 (?)	39			2 500	538	3.00	2 010	2.34	182	729	308	1 212
	" " "												2 500	698	3.90						
2	Provo, Utah	1891	14	3.70	1⅛	Redwood	⅜-in. plain.	5 500	18	95	2.33	172	2 500	402	3.00	273	2.46	188	729	305	880
	" "												1 367	402	3.00	.....	2.00	211	1 196	.....	.....
3	Caldwell, Idaho	1900	54	0.18	1⅛	Pine	⅜-in. plain.	6 300	.....	.....	2.73	165	1 344	396	3.00	272	2.00	206	1 108	353	1 349
4	Butte, Mont.	1902	84	9.00	1⅛	Redwood	⅜-in. upset.	.....	6	83	0.00	50	515	3227	1.64	1 005	1.30	384	1 896	169	676
	" "										2.44	302	3 563	461	3.9	864	3.04	325	900	299	1 156
5	Bear Valley, Cal.	1903	62	0.41	2.00	Redwood	⅜-in. upset.	17 900	12	98	2.00	165	3 794	497	4.06	2 400	2.60	151	900	251	1 004
	" "			2.00									3 794	508	4.00	960	3.58	150	493	196	787
6	Logan, Utah	1903	18	1.90	1⅛	Redwood	⅜-in. plain.	5 300	12	18	4.00	58	5 08	300	5.08	728	1.91	100	393	100	1 417
	" "												5 08	300	5.08	576	3.30	99	325	154	896
7	Los Angeles, Cal.	1905	94	1.00	1⅛	Redwood	"	9 000	12	95	4.00	88	1 503	369	4.92	1 600	2.58	187	414	496	785
	" "												1 503	369	4.50	1 600	2.58	161	496	392	610
8	Astoria, Ore.	1906	18	7.50	1⅛	Fir	⅜-in. upset	9 000	12	95	2.35	175	1 106	369	5.56	1 600	2.75	188	891	297	1 358
	" "												1 506	382	4.76	909	4.10	128	882	213	570
9	Hollister, Cal.	1906	12	.....	1⅛	Redwood	⅜-in. rolled thread.	6 000	10	98	2.73	100	599	169	8.59	1 125	3.48	109	575	206	1 417
	" "												599	716	7.30	909	5.36	126	696	172	918
	" "												705	182	7.30	1 272	3.01	119	600	208	1 490
	" "				1⅝								695	307	6.38	318	4.86	128	600	167	889
10	St. Paul, Minn.	1906	48	1.50	1⅛	Fir	⅜-in. plain.	7 500	14	5	4.00	95	698	80	10.45	2 450	2.96	128	1 196	141	563
	" "												911	114	7.32	700	4.36	98	182	77	366
11	West Los Angeles, Cal.	1896	90	7.50	1⅛	Redwood	⅜-in. rolled thread.	11 800	12	90	.....	.....	1 502	276	6.49	1 800	3.25	111	446	290	882
	West Los Angeles, Cal.	1897	72	5.10	2.00	Fir	⅜-in. upset.	18 400	5.25	85	8.90	105	2 870	355	4.33	525	3.69	105	660	197	788
12	Ogden, Utah										0.00	100	4 490	374	4.33	1 000	3.11	128	409	156	487
	" "			2.00							2.73	100	4 490	374	3.78	573	3.88	128	409	143	447
	" "										8.94	117	6 471	389	3.77	706	3.42	164	492	170	454
13	West Los Angeles, Cal.	1898	14	7.50	1⅛	Redwood	⅜-in. rolled thread.	5 500	10.00	20	.....	.....	605	194	0.88	1 125	2.81	98	534	207	1 264
	West Los Angeles, Cal.																				

* Oval bands, 1¼ in. × 4 in., were used.

From the many existing lines of stave pipe, thirteen have been selected for presentation. These, it will be observed, cover a great range in both size and pressure, and are, with some exceptions, characteristic of the best practice prevailing at the time of their construction. There would be little gained by pointing out defects in design of a nature that would be patent to any intelligent person, for which reason no cognizance is taken of any existing pipes that have been designed or constructed foolishly.

Table No. 5 is believed to be self-explanatory, in the light of the previous discussion. The chief interest centers in the unit band strains used, the probable effect upon these of the swelling of the staves, and the necessary compressive resistance of the staves. Of the latter, it is, of course, the maxima that are chiefly interesting, and these, for reasons already made plain, are usually found in pipes of relatively small diameter, since with large pipes other considerations lead to lower values.

Band Strains.—The factors used in proportioning the spacing of the bands, disregarding the strains induced by swelling timber, vary from 1.64 to 10.45, while the factors resulting from a consideration of the stave swelling range from 1.30 to 4.35. This latter source of strain seems to have received no recognition in design previous to 1895. Since then, in the design of the Los Angeles, Astoria, Hollister, and West Los Angeles lines, a modification of the band spacings has been made for the lighter pressures in recognition of this strain, it being, however, ignored where spacings became less than 8 or 9 ins. On the St. Paul line, while it is not clear what general assumptions have governed the determination of the band spacings, the factors used indicate some recognition of these strains.

Any estimate of the strains due to the swelling of the staves under the maximum band spacing on the Provo line has been omitted. With a spacing of 18 ins., under a water pressure of 25 ft., a stave $1\frac{3}{8}$ ins. in thickness, a pressure of 211 lbs. per lineal inch of band on the stave and a lack of hard cinching during construction, it is doubtful if such a strain exists to a considerable extent.

The Caldwell, or Phillis, pipe was a bold design as originally built, and is the only instance known to the author where pipe bands were actually broken by the swelling of the staves. The lumber used was Eastern Oregon mountain pine. A factor of only 1.64 seems to have

been used in the spacing. On the assumption that stave swelling produced a strain of 100 lbs. per square inch of contact between staves, doubtless a very conservative assumption with this class of lumber and size of pipe, and, with 6-in. band spacing, this band factor would be reduced to 1.30. Uncertainty as to the exact tensile strength of the material used, and the use of a shoe of the type shown in Fig. 4, with the probable resulting bending of the band under the nuts, is doubtless sufficient to account for the rupture of the bands. The pipe being of large diameter, the pressure of the bands upon the staves is seen to have been too low to admit of any further yielding and consequent partial release of the band strain.

The difficulty with this pipe is said to have been remedied by largely increasing the number of bands.

Compressive Resistance of Staves.—The highest degree of compressive strain between band and staves necessary for the maintenance of a tight pipe seems to have been used at Provo, and the results are instructive. The ready stripping of threads, due to poorly fitting nuts, prevented very hard cinching and satisfactory compression of the stave under the band. The timber was seasoned redwood. The pipe, a gravity line, is closed at the end, feeding direct into the distributing system. The use of hydrants for street sprinkling and other purposes caused a water pressure at the lower end of the line of 30 lbs. above the normal, making the pressure on the staves 290 lbs. per lineal inch of band under these conditions, or 1 550 lbs. per square inch of band contact. Leakage resulted, which was remedied by the addition of more bands, the re-cinching of those already on, and the partial prevention of the water hammer. The upper section of the pipe, not being subject to any considerable increase of pressure over that for which it was banded, has never given any trouble, although, as seen in Table No. 5, the normal pressure on the staves cannot be much less than 211 lbs. per lineal inch of band, or 1 126 lbs. per square inch of band contact.

On the Butte line the staves are depended upon to afford a permanent resistance against band pressure of not less than 900 lbs. per square inch of band contact. At Astoria the fir staves must resist a pressure of not less than 832 lbs. per square inch of band contact. Both of these lines have been unqualifiedly successful, and the latter line, especially, has from the first been remarkably free from leakage.

The former, by reason of the yet uncompleted condition of the storage dam which impounds the water from which the pipe is supplied, has not as yet been subjected to quite all the pressure for which it is designed.

In the smaller pipes subsequently built at Hollister, it will be noticed that much additional steel has been used in order to secure greater area of contact between bands and staves and thus keep the necessary compressive resistance of the staves down to from 600 lbs. to 686 lbs. per square inch. At the present time the same results might be achieved at considerably less cost by the use of bands of oval instead of round section. Such a course, as tending toward conservatism in a matter still somewhat imperfectly understood, and to partially nullify the effects of any lack of skill in erection, the author believes to be advisable in the design of the smaller sized pipes.

Construction Details.—There are but few structural details of this class of pipe in which there is sufficient diversity of practice to warrant any discussion. The butt-joint connection, the use or omission of a bead along one edge of the stave and the coupling shoes are the only features which need be considered.

Butt Joints.—It is the prevailing practice to make the connection between the butts of connecting staves by the snug insertion of a No. 12 or No. 14 steel plate about 1½ ins. in width, and slightly longer than the width of the stave where inserted, the plate extending slightly less than half its width into each stave. For this, in some light pressure pipes, a plate of hard wood has been substituted. The objection to the latter lies chiefly in the difficulty of forcing a thick wooden plate into the adjoining stave sufficiently to secure a tight joint, and in securing the perfect fit evidently necessary. The existing general preference for the steel plate seems justified.

Plain vs. Beaded Edges.—The use of a bead on the stave edge is in no way vital to the success of a pipe, but seems to have strong points in its favor. If there is any irregularity in the edge of the plain stave, with band spacing suitable for light or moderate pressures, it is not possible and certainly not economical to induce sufficient fiber compression between the staves to take up those irregularities. By the use of a slight bead the compression due to cinching is at first concentrated on the bead, forcing it into the adjoining stave, and thus a uniformly tight seam is secured without the necessity for hard

compression throughout the entire contact area that exists in the other case. Furthermore the bead adds nothing to the cost of the stave.

Coupling Shoes.—Not a little ingenuity has been displayed in devising various types of coupling shoes, the desideratum being that with the least cost the shoe should have an ultimate strength fully equal to that of the band, a sufficient and properly distributed bearing surface to withstand high strains without destructive crushing of the

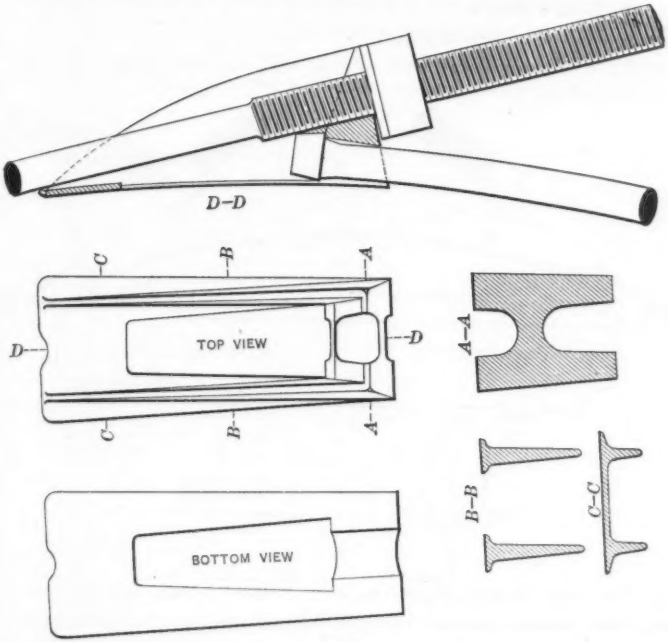


FIG. 1.

stave, and admit of speedy placing and the ready adjustment of the band during erection.

In the following discussion only those types are considered which have separate characteristics, are the better of those that have been used, and which have already met, or promise to receive, the greatest measure of favor.

The various devices in use may be divided, with reference to the manner of engaging the two ends of the band, into two general classes:

(1) Those which engage the two ends in the same transverse plane, as Figs. 1, 2 and 3.

(2) Those in which the ends are not engaged in the same transverse plane, as Fig. 4.

With reference to the materials of which they are made, they may be divided into:

(1) Forged, as Figs. 2 and 3.

(2) Cast, as Fig. 4.

(3) Malleable cast, as Fig. 1.

Fig. 1 is the general form of shoe that has been largely used by

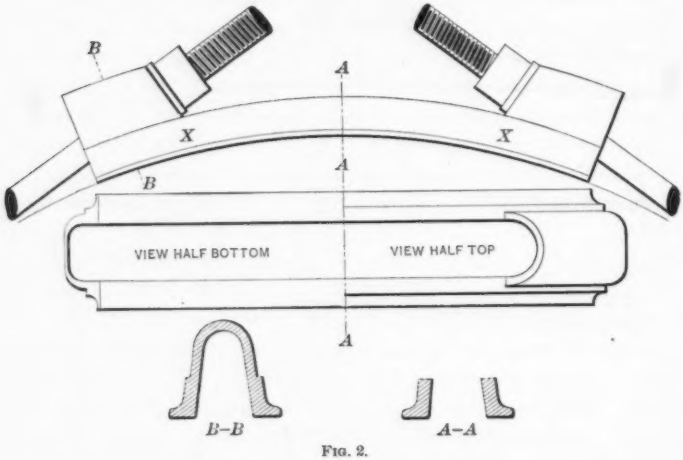


FIG. 2.

the Excelsior Wooden Pipe Company, it having been evolved from, and being representative of, the type originally used in the construction of the Denver lines. When properly proportioned this shoe admirably meets all the requirements for a successful connection, and, in the economical distribution of the material for resisting the strains imposed, leaves little to be desired, and possesses much to be admired. It will be noted that by the use of a T-head, the nut is brought as low as possible and the resulting moment tending to produce rotation about the center of the head bearing is thus reduced to a minimum. The length and ample bearing of the shoe enables the stave to resist this tendency without destructive pressure. The flanges on the lower

edges of the ribs afford bearing surface and give sufficient sectional area to resist the tensile strains here existing, while, in height, the ribs are well proportioned for transmitting the band strain to the staves. It will also be observed that the shoe permits the use of the wrench without interference. The feature most open to criticism in the design of this shoe as generally used is the tendency to make insufficient allowance in its weight for the deterioration of such light sections.

Fig. 2 shows a shoe of a type that has been used in a number of instances on the Pacific Coast. It is a forging from a rolled section. The length of the shoe in the rear of the nuts is wholly insufficient to

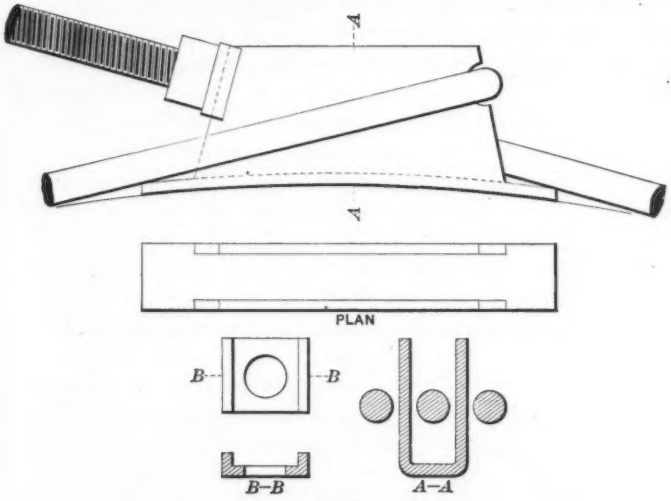


FIG. 3.

afford the proper degree of bearing surface on the stave to safely resist the pressure; and the bending strain at *X*, due to the depressing of the end of the shoe into the stave, can only be resisted by the use of a much heavier section than the tensile strains alone require, or prevented by giving more supporting area under the ends. It is evident that the fault lies in the use, unavoidable here, of low connecting ribs.

Fig. 3 is a forged shoe of the type used on the recently completed work of the Pioneer Power Company, at Ogden, Utah.* In most

* *Transactions*, Am. Soc. C. E., Vol. xxxviii, p. 270.

respects the form is evidently well calculated to economically resist the imposed strains; but, as it necessitates the use of a welded loop on one end of the band, the shoe can scarcely compare in economy with some of the other types, unless indeed the relative cost is very largely influenced in its favor by royalty charges on the other shoe. The details of the loop bearing on the shoe are perhaps not beyond

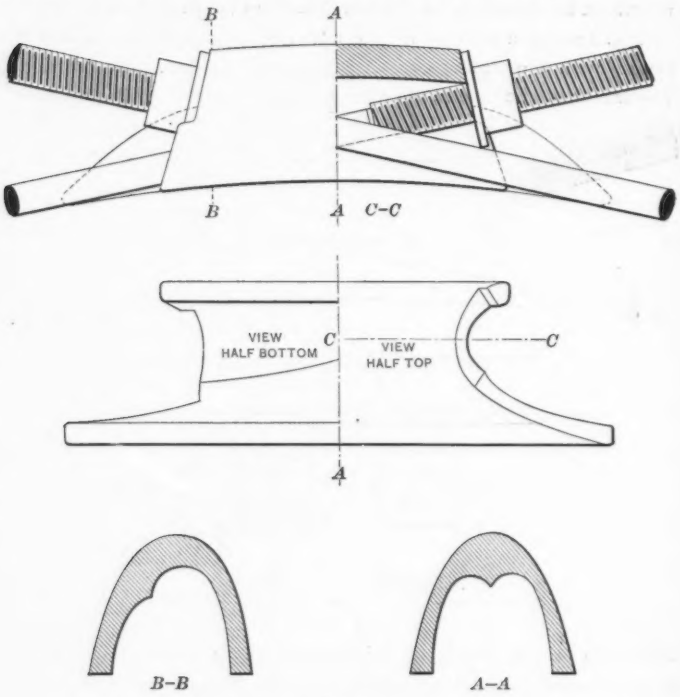


FIG. 4.

the suggestion of improvement, as there appears to be possible lack of stiffness, which, however, could be readily remedied by the insertion between loop and shoe of a properly designed compression lug of cast iron. It would also appear that the cost of the entire shoe might be somewhat reduced without sacrifice in other respects by modifying the design and making it of cast or malleable cast iron,

for which materials the general shape of the shoe, as affecting the strains, seems especially well suited.

Fig. 4 is of that class which does not engage the ends of the band in the same vertical plane. There being thus introduced a cross-strain or tendency to rotate about an axis vertical to the center of the shoe, it is difficult to devise a really efficient and economical design. It is usually sought to resist this tendency to rotate by means of the friction afforded by long tapering extensions at each end of the casting, as shown in the figure. This device has generally been found insufficient, hard cinching usually resulting in the breaking of these tail pieces or the rotating of the shoes and the bending of the bolts. These difficulties can, of course, be corrected by the use of very large, heavy shoes, but with a resulting cost much beyond that of other and better types.

This general style of casting seems to have been the first used in stave pipe construction with round bands, and has had quite an extended application in recent years, though frequently with unsatisfactory results. The particular design shown is that adopted in the construction of the Los Angeles outfall sewer, in the spring of 1894, and in detail is the best of its class that the author has seen. Nevertheless, it was found to possess the defect inherent in the type, many having broken under the reputed light and insufficient cinching used on that work.

In conclusion, it appears to the author that the essential requirements of a safe and economical design are much more successfully worked out in Fig. 1 than in any of the others.

The Economy of its Use.

In seeking to set forth clearly the real place of stave pipe in the economic design of pressure conduits, it is essential that the conspicuous types of pressure pipes be briefly considered in their relation to each other. The three varieties to be contrasted herein are stave, steel riveted and cast iron. Welded pipe is omitted because it occupies an intermediate position and does not affect the merits of the discussion. The comparison will be confined to the pressure range of practical stave pipe construction, say, not to exceed 100 lbs. per square inch, for which pressure each of the classes mentioned may be assumed to be wholly applicable.

Previous to argument, the relative standing of each, in the order of their merit with reference to the three most important qualifications, the author tabulates as follows:

	Cost.	Life.	Capacity.
(1)	Stave.	Cast iron.	Stave.
(2)	Steel riveted.	Stave.	Cast iron.
(3)	Cast iron.	Steel riveted.	Steel riveted.

If the quantity of water delivered, instead of the diameter, were made the common basis of comparison for the different pipes, the capacity would become a function of the cost, an aspect briefly considered later. For the present they will be considered separately.

Life.—Passing temporarily over the question of cost and taking up that of comparative duration, it may be assumed at once that cast iron should be given the preference, not, indeed, as conclusively proven by experience, but as in every way probable, since the bands of the stave pipe, excepting, perhaps, in the larger sizes, can hardly be supposed to have the same degree of endurance as the thick shell of the cast pipe.

In placing steel pipe last, the author is influenced by the following considerations:

(1) That the sheet metal from which the pipe is made is of less thickness than the diameter of the stave pipe bands, a condition always existing in steel pipes subject to the comparatively light pressures here considered.

(2) That the same degree of care in securing protection of the metal can be exercised in both cases.

(3) A properly proportioned steel pipe does not eventually fail by bursting, but by the formation of rust holes and attendant leakage. The considerable multiplication of such holes soon causes a new pipe to be cheaper than the necessary repairs, even though $\frac{995}{1000}$ of the metal in the pipe may be as good as when it was laid. The life of a steel pipe, therefore, without material error, may be said to be measured by the life of its weakest spots.

(4) The life of a stave pipe is probably determined by the life of the bands; and the life of the bands is determined, not by the time necessary for the formation of local rust pits, even though they are very deep, but by the reduction of the entire band section until its ultimate strength is exceeded by the strain, say to less than one-fourth

its original section. It seems clear that the time requisite to accomplish this degree of deterioration in the sections generally used must be many times that necessary to accomplish the destruction of the average riveted pipe.

(5) Many cases on the Pacific Coast might be cited where steel pipes of the lighter gauges, though carefully coated with asphalt, and apparently laid with reasonable care, have rusted through in from eighteen months to three years, and have been shortly afterward abandoned.

(6) Should a perfect and reasonably cheap protective coating for steel ever be discovered—an improbable assumption—no single class of pipe would have much advantage over another in respect to durability.

(7) It is certainly in accord with universal engineering experience to assume that wood, under the conditions prevailing in proper stave pipe construction, is practically indestructible ; and much direct evidence in harmony with this assumption has accumulated from the many instances of the use of stave and other wood pipe constructions which have done service in America for from twenty to fifty years, and, so far as the author knows, without an instance of failure from the decay of the staves, where the proper requirements were observed.

The author does not wish to be understood as intimating that steel pipe is always short lived. On the contrary, many such pipes, where conditions are favorable, have been doing excellent service for many years; but the exceptions are instructive, and fully vindicate the position assumed by many engineers, who, for permanent work, have recognized the necessity for a considerable thickness of metal, independent of the demand for a sufficient factor of safety against bursting, and who accord little favor to pipes of very light gauge.

The foregoing seems to the author to be ample justification for placing the stave pipe far in advance of the steel pipe for durability under average conditions.

Capacity.—The past few years have added much to the knowledge of engineers concerning the carrying capacity of cast-iron and particularly of steel riveted pipes of various diameters. The relative values of each class, as economic carriers of water, are better understood than ever before. The general result of experiments on cast-iron pipe has been to prove the value of the Kutter formula in showing the value of

"n" to be practically a constant for any given diameter, degree of surface roughness and velocity of flow. In the case of steel riveted pipes, whether built with cylindrical or taper joints, with few exceptions, the results indicate that the Kutter formula does not apply, and that for the ordinary ranges of velocities, say from 3 to 6 ft. per second, for clean pipes the coefficient c in the formula $v = c\sqrt{r\,s}$ is nearly a constant for all diameters; and if the experiments on the Portland, Ore., pipes are excepted, because of inability to harmonize them with others, it is not clear that the results are much affected by variations in the thickness of the plates, within the range of ordinary usage.

These experiments, while still leaving much to be desired before attempting the formulation of any positive rules for the exact preliminary determination of the rate of flow in any given case, a result which the author believes will not be accomplished save within limits of very narrow application, because of the usual unavoidable lack of similarity in the influencing physical conditions, are sufficient to accomplish the complete upsetting of many previously conceived ideas regarding the laws of flow in this class of pipe. The failure of "c" to increase as the diameter increases places the value of this pipe, as an efficient water carrier, at least for the large diameters, in a relation to pipes having approximately smooth interiors, totally different from that which it has previously been accorded.

The dissipation of the once prevalent idea that wrought-iron and steel pipes are not subject to tuberculation, and the later conviction that in this respect they have little or no advantage over cast iron have also done much to make possible a better estimate of the real merits of this pipe.

The author regrets that as yet so few experimental determinations of the carrying capacity of stave pipe under varying conditions of diameter and grade have been made. In engineering literature he knows of only four in which the proper conditions have been sufficiently observed to render them worthy of mention. They are as follows:

(1) An experiment on a long line of 30-in. pipe at Denver, briefly mentioned by J. D. Schuyler, M. Am. Soc. C. E.* In this case, with a mean velocity of about 2.33 ft. per second, the derived value of n in the Kutter formula was found to be a little less than 0.010.

* *Transactions*, Am. Soc. C. E., Vol. xxxi, p. 144.

(2) An experiment by the author on an 18-in. pipe,* in which the value of c in $v = c\sqrt{r\,s}$ was found to be 133, with a mean velocity of 3.60 ft. per second. This result corresponds to a value for n in the Kutter formula of a little less than 0.010.

(3) Experiments on a section of the 6-ft. pipe of the Pioneer Electric Power Company, at Ogden, Utah, described by Charles D. Marx, M. Am. Soc. C. E.; Charles B. Wing, Assoc. M. Am. Soc. C. E., and Leander M. Hoskins.† These results gave average values for c as follows:

Velocity in feet per second.	Corresponding value of c.
1.0	100
2.0	115
3.0	122
4.0	125

The values of n corresponding to these results vary from 0.012 to 0.015.

(4) Experiments by the author on a line of 14-in. pipe,‡ in which the values of c averaged as follows:

Velocity in feet per second.	Corresponding value of c.
0.7	102
1.2	111
1.5	112

The values for n corresponding to these results vary from 0.0107 to 0.011. The velocities, it will be observed, are all very low.

The results of the Ogden experiments are so much at variance with the great preponderance of credible evidence bearing on this question, that, without wishing to seem to discredit them, the author awaits further verification of the results before accepting them as conclusive.

In Table No. 6, showing the values of c in the formula $v = c\sqrt{r\,s}$, for clean pipes of staves, cast-iron and lap-riveted steel, the values for the stave and cast-iron pipes are deduced by aid of the Kutter formula, assuming a value for n of 0.010 for the stave pipe, of 0.011 for the cast pipe when clean, and 0.014 when tuberculated, a velocity of flow of 3 ft. per second being assumed. For steel riveted pipes the uniform value of 111 is given for c for all diameters, and a

* *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 26.
† *Transactions*, Am. Soc. C. E., Vol. xl, p. 471.
‡ *Transactions*, Am. Soc. C. E. Vol. xi, p. 545.

deduction of 20% is made in determining the values for tuberculated pipes.

The calculated values are for the most part interpolated from tables, and may be slightly in error in the last figure.

TABLE No. 6.—VALUES OF c IN THE FORMULA $v = c\sqrt{r\,s}$ FOR CLEAN PIPES OF WOOD, CAST IRON AND RIVETED STEEL; AND FOR CAST-IRON AND STEEL RIVETED PIPES WHEN TUBERCULATED.

Diameter.	Stave.	Cast Iron.		Steel Riveted.	
	$n = 0.010$.	Clean. $n = 0.011$.	Rough. $n = 0.014$.	Clean.	Rough.
12	119	105	77	111	89
18	130	117	86	111	89
24	137	123	92	111	89
30	143	129	97	111	89
36	148	133	101	111	89
42	152	136	105	111	89
48	154	138	108	111	89
54	157	140	110	111	89
60	159	142	112	111	89
66	161	144	114	111	89
72	163	146	116	111	89

If the discharging capacity of the stave pipe of any diameter is designated as 100, the relative discharging capacities of the others will be as follows:

TABLE No. 7.—RELATIVE DISCHARGING CAPACITIES OF PIPES, STAVE PIPE BEING TAKEN AS 100.

Diameter.	Stave.	Cast Iron.		Steel Riveted.	
		Clean.	Rough.	Clean.	Rough.
12	100	88	65	93	74
18	100	90	66	86	69
24	100	90	67	81	65
30	100	90	68	78	62
36	100	90	69	75	60
42	100	90	69	73	58
48	100	90	70	72	58
54	100	89	70	71	57
60	100	89	70	70	56
66	100	90	71	69	55
72	100	90	71	68	54

If the premises are correct, and they are believed to be in harmony with present knowledge, these results are of a startling nature. Clean cast-iron pipes would seem to have about 90% of the carrying capacity of stave pipes, while if seriously tuberculated, a condition which usually prevails after a few years of use, they discharge only about two-thirds as much as stave pipe of the same size.

The steel pipe discharges when clean from 93% in case of a 12-in. pipe to 68% in case of a 6-ft. pipe of the amount which might be expected from stave pipes of the same sizes, while if the steel pipe is tuberculated to an extent that may readily occur in from ten to fifteen years of use, these discharges may fall to 74% and 54% respectively.

Omitting other considerations, is not the value of a pipe line investment proportional to its delivering capacity? Do not these percentages, then, represent approximately the relative values of these different classes of pipe as investments?

Cost.—Variability in market quotations on materials, freight rates, wages, the effect of geographical location on these, the conditions affecting haul and the manner of executing the work make it impossible to deduce an accurate comparison of cost which would admit of general application. For present purposes, however, it is not necessary to attempt more than to convey a general idea of the order of the respective costs of the three classes of pipe considered, at the terminal points designated. For this purpose Tables Nos. 8 and 9 have been prepared with considerable care.

It is assumed that the stave pipe is designed in accordance with the formulas previously deduced, an assumption which somewhat increases the cost, particularly for light pressures, above that which would result were the bands spaced in accordance with the formula more commonly used.

The steel pipe is supposed to be double riveted on the straight seams and single riveted on round seams, as ordinarily built, and coated with asphalt. The mill price for sheet steel is taken at from 1.60 for No. 14 plate to 1.25 for thicknesses greater than No. 8.

The cast pipe is supposed to be proportioned as to thickness by the formula of the Warren Foundry, and the prices assumed per ton are $19 at Chicago and $26 at San Francisco, the latter figure being the lowest yet quoted there.

TABLE No. 8.—Comparative Cost of Pipe at Chicago.
(Including Laying, but not Hauling.)

Nominal diameter.	Stave.				Steel Riveted.								Cast Iron.			
	25-ft. head.	50-ft. head.	100-ft. head.	200-ft. head.	No. 14, B. W. G.	No. 12, B. W. G.	No. 10, B. W. G.	No. 8, B. W. G.	No. 6, B. W. G.	¼ in.	⅜ in.	⅝ in.	25-ft. head.	50-ft. head.	100-ft. head.	200-ft. head.
12	.42	.49	.63	.85	.32	.38	.44	....	....	....	....	....	.73	.77	.84	1.00
18	.69	.80	1.02	1.46	....	.57	.65	.78	.98	....	....	....	1.29	1.35	1.46	1.70
24	.79	.91	1.14	1.61	....	....	.85	1.04	1.28	1.55	1.99	....	1.91	2.00	2.18	2.55
30	.96	1.12	1.44	2.06	....	....	....	1.27	1.59	1.93	2.46	3.04	2.67	2.80	3.07	3.61
36	1.19	1.40	1.82	2.65	....	....	....	1.55	1.93	2.30	2.92	3.58	3.47	3.67	4.06	4.85
42	1.40	1.68	2.23	3.33	....	....	....	1.61	2.18	2.66	3.37	4.12	4.42	4.69	5.22	6.28
48	1.55	1.85	2.46	3.67	....	....	....	....	2.48	3.03	3.83	4.66	5.50	5.84	6.53	7.92
54	2.23	2.62	3.43	5.02	....	....	....	....	2.80	3.41	4.29	5.21	6.65	7.10	8.00	9.78
60	2.85	3.35	4.37	6.40	....	....	....	....	....	3.79	4.75	5.74	8.04	8.63	9.80	12.13
66	3.21	3.81	5.00	7.38	....	....	....	....	....	4.35	5.21	6.29	9.51	10.16	11.55	14.05
72	3.65	4.38	5.83	8.73	....	....	....	....	....	4.52	5.66	6.83	11.32	12.00	13.26	16.00

TABLE No. 9.—Comparative Cost of Pipe at San Francisco.
(Including Laying, but not Hauling.)

Nominal diameter.	Stave.				Steel Riveted.								Cast Iron.			
	25-ft. head.	50-ft. head.	100-ft. head.	200-ft. head.	No. 14, B. W. G.	No. 12, B. W. G.	No. 10, B. W. G.	No. 8, B. W. G.	No. 6, B. W. G.	¼ in.	⅜ in.	⅝ in.	25-ft. head.	50-ft. head.	100-ft. head.	200-ft. head.
12	.37	.45	.61	.94	.45	.52	.60	....	....	....	....	....	.94	.99	1.09	1.31
18	.58	.71	.96	1.47	....	.77	.88	1.04	1.30	....	....	....	1.65	1.73	1.89	2.21
24	.76	.96	1.35	2.12	....	....	1.01	1.35	1.67	1.97	2.51	....	2.50	2.62	2.86	3.37
30	.83	1.03	1.43	2.23	....	....	....	1.64	2.04	2.45	3.10	3.79	3.52	3.70	4.07	4.81
36	1.02	1.25	1.83	2.90	....	....	....	1.80	2.44	2.92	3.67	4.49	4.60	4.87	5.40	6.50
42	1.23	1.58	2.28	3.69	....	....	....	2.27	2.80	3.37	4.24	5.12	5.87	6.25	6.97	8.43
48	1.34	1.73	2.51	4.07	....	....	....	....	3.14	3.80	4.78	5.78	7.33	7.80	8.73	10.64
54	1.94	2.45	3.49	5.52	....	....	....	....	3.55	4.32	5.37	6.47	8.86	9.47	10.69	13.15
60	2.44	3.09	4.39	7.00	....	....	....	....	....	4.87	5.95	7.24	10.73	11.54	13.14	16.33
66	2.79	3.57	5.14	8.26	....	....	....	....	....	5.43	6.54	7.81	12.70	13.69	15.45	18.92
72	3.22	4.15	6.04	9.78	....	....	....	....	....	5.90	7.09	8.50	15.12	16.05	17.78	21.53

The figures are supposed to include only the principal common items of expense, with no profit to the contractor. They are therefore, perhaps in every case, somewhat below probable cost, and are intended for use by way of comparison only.

A contrast of actual quotations for particular cases would in almost every instance show a greater advantage to the stave pipe than the tables indicate. Especially would this be true where a considerable haul would be necessary, or where the work is far removed from pipe shops and of insufficient magnitude to justify manufacturing the riveted pipe on the ground, or where the site is difficult of access. The tables indeed assume the most favorable conditions for the use of the steel riveted or the cast pipes.

Conclusion.—If, then, stave pipe stands unquestionably first in point of both first cost and carrying capacity when contrasted with the two other classes of pipe usually considered, and second only to cast iron in length of life, does it not logically follow that it is destined to a greatly extended use? and is it not clear, that though the great saving in first cost incident to local causes has fostered its rapid introduction in the West, yet the field of its economic usefulness is by no means compassed by such narrow limits? If these queries are answered in the affirmative, is it not deserving the careful consideration of engineers who conscientiously and studiously seek a wise economy in the design and execution of hydraulic works?

DISCUSSION.

Mr. Tillson. GEORGE W. TILLSON, M. Am. Soc. C. E.—Mr. Patten's* statement shows that wood which is alternately wet and dry, rots very rapidly in a climate like that of Wyoming. In the case he describes, where the pipe was running at times not much more than half full, such results would naturally be expected. The author evidently appreciates fully the danger in that respect, because he specifies that the staves shall be so thin that the water will thoroughly permeate them.

The only explanation the speaker can give for this rapid decay is that the wood is dry so long that it becomes thoroughly seasoned, or thoroughly free from moisture, and then, when rain occurs, such wood is in the right condition to absorb a large amount of moisture. In a short time it becomes dry again, and so goes on in that way alternately thoroughly wet and thoroughly dry.

Several instances of such decay have been noticed by the speaker. In Omaha, Neb., a lot was being graded, and, in order to work grading machines to advantage, it was necessary to grade the earth over an adjacent wooden sidewalk. When the work was completed the sidewalk was cleaned off, and, although the earth had only been on the walk two or three months, the planks had decayed appreciably.

In wooden block pavements laid in Omaha, although the spaces between the blocks were filled with sand, and the interstices with tar, in a year and a half or two years, cedar blocks began to decay around the edges, and in three years cypress blocks were almost entirely gone.

Mr. Hering. RUDOLPH HERING, M. Am. Soc. C. E.—Questions as to the durability and capacity of stave pipe will have to be settled by a little longer experience than has as yet been obtained. Cast iron and steel are more expensive on the Pacific slope than in the East, while wood is cheaper. For that reason they have manufactured a good deal of stave pipe, and have had more experience with such pipe in that country than in the East; and while it is somewhat courageous in the author to take the position that wood will last longer than iron, yet there is much truth and force in his reasons. In California the speaker has seen wood pipe that had been in the ground thirty years, and which was as good as the day it was put in. He has also seen wrought-iron pipe hardly $\frac{1}{4}$ in. thick that had been used in the ground, and, afterward for two years had been lying in the field, and on which scarcely any rust could be seen, merely a discoloration.

The speaker believes that there is a considerable future for stave pipe, provided that great care is taken in the selection of the materials, in their manipulation and in the construction. The question of rot

*See p. 65.

is answered in this way: If the pipe is painted inside, the wood will almost surely rot out; it should not be painted or covered with any oily material, because the water which is in the pipe under pressure should go through the wood, and keep it thoroughly wet all the time, thus preventing rot. The pipe before mentioned by the speaker had not been painted inside; he was shown pipes that had been so painted, and they had rotted in a few years. It is necessary, of course, to have the water under pressure constantly, so that it will ooze through the pores of the wood, and keep it in a condition similar to that which protects wood under water. The loss of water by the oozing is insignificant. Mr. Hering.

It has been found that bands having a circular or elliptical section are very much better than the flat bands formerly used, because for the same quantity there is a smaller surface of metal exposed to corrosion. Of course, a great deal depends upon the care with which the material for the bands is made, and then upon the care with which the bands are coated and fastened around the pipe. The speaker saw in Tacoma some of these bands broken while they were being put around the pipe, thus showing that they had been improperly made. Great care must be taken in all the details of manufacture in order to make a successful stave pipe. The speaker believes, however, that if the work is well done, the Pacific Coast, at least, has a means of laying and maintaining water pipes at a great deal less expense than if either steel or cast iron were used.

The wrought-iron pipe before mentioned was used by the Spring Valley Water Company in San Francisco. The chief engineer there maintained that wrought iron was better than steel, because, if the material was sufficiently manipulated, so that practically no uncombined carbon was left therein, there would be less occasion for rust. The uncombined carbon in the steel and in the cast iron, in connection with the carbonic acid in the air and in the water, causes electrical action, and therefore corrosion. The specifications required a very severe treatment in the manufacture, rolling over and over many times, so that a high degree of homogeneity was obtained, and electrical action in the material was practically prevented. Cast iron apparently does not corrode so much as wrought iron, but this is due to the fact that it is protected on the outside by magnetic oxide. If that is removed, cast iron will corrode more quickly than homogeneous steel or wrought iron.

In the speaker's opinion there is no question but that the carrying capacity of a wooden pipe, made of staves which have been planed, will be greater than that of a riveted steel or cast-iron pipe. There have been so many observations to confirm this that it cannot be questioned so long as the pipe is kept in good condition. However, some change in that condition may take place. For instance, a slimy coating may

Mr. Hering. become attached to the wood, or plants grow thereon, causing a great resistance and consequently a diminished flow.

In reply to a question the speaker stated that he had never heard of any trouble caused by any chemical action of the iron in eating the wood away.

Mr. O'Rourke. J. F. O'ROURKE, M. Am. Soc. C. E.—The author believes that it is profitable to limit the use of stave pipe to pressures lower than 100 lbs. per square inch. In a 6-ft. pipe, 100 lbs. pressure would be equivalent to the maximum strain allowable on a steel shell $\frac{1}{4}$ in. thick, or about 15 000 lbs. per square inch. In a 6-ft. pipe, omitting the strains due to cinching and to the swelling of the staves, and considering only the strain caused by a pressure of 100 lbs. per square inch, the bands would be so numerous that their cost would probably be as great as that of a cast-iron pipe. The author, therefore, should fix more closely the economical limit as to the diameter of the pipe and the pressure at which it can be used.

The limit of pressure fixed by the author seems to be too great, and, so far as durability is concerned, the speaker takes issue with him, because of the difficulty in protecting the bands and because such pipes are not yet cheaper or more economical than cast-iron pipe under certain conditions. They may be cheaper than cast-iron pipe in first cost, but they are not as long lived.

The author should be a little cautious in stating that steel bands, hammered around the wood and buried in the ground, will last longer than steel pipe treated in the shops.

A few years ago the speaker had occasion to remove from Broadway, New York City, some wooden pipe, which had been put down by the old Manhattan Water Company. It had been in the ground in the neighborhood of a hundred years, and was a little soft, but not at all decayed. Its condition was just what would naturally be expected in wood that had been so long in a damp, but not wet, condition. That is, the condition of wood which has been in comparatively moist earth, and which has not been exposed to the air.

A similar case of old wood, under like conditions, was found in the summer of 1898, in an old building at the corner of Gold Street and Maiden Lane, New York City. The bottom of the wall consisted of oak mud-sills, about 5 or 6 ft. long and 6 ins. thick. These planks were, perhaps, less than a foot above the water and were quite sound. On top of the mud-sills, hewn timber, about 24 ins. wide and 10 or 12 ins. thick, was laid the full length of the wall. This timber was fully 18 ins. above the ground-water. It was simply in moist clay and was perfectly sound, although the building was more than a hundred years old.

So far as stave pipe is concerned, when it is well buried in moist earth the speaker does not think there is any serious danger of the

wood rotting. The danger is confined entirely to the corrosion of the bands, as the author states. Mr. O'Rourke

It is stated in the paper that the thickness of the staves should be limited so that they will become thoroughly water-soaked. The speaker believes this dimension to be very large.

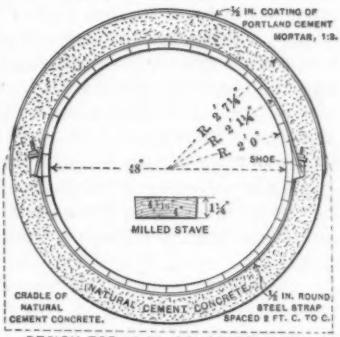
In the summer of 1898, the speaker put down some wooden caissons which were similar to stave-pipe in construction, except that the rings were on the inside. The staves were of yellow pine, very rich in pitch, and were $3\frac{1}{2}$ ins. thick. The water in the ground around the caissons was kept below its original level by pumping, to about 6 ft. from the surface of the cellar. The caissons were sunk about 30 ft. deeper than this, and some of them had been in the ground for nearly a week before the pig iron and air shafts were taken out and the interiors made visible. It was found that the water had penetrated the $3\frac{1}{2}$ ins. of rich pine, and that it indicated distinctly the outside water-level.

The speaker thinks, therefore, that the question of making the staves thin enough to allow the water to soak to the outside need not give much trouble. The author recommends staves $1\frac{3}{4}$ ins. or 2 ins. thick to permit of complete saturation; in the opinion of the speaker the staves might be a foot thick, if such a thickness were ever necessary, and that still the water would soak through to the outside and always keep the timber wet while the pipe was full.

The speaker considers that such an excessive thickness would never be called for, and only mentions it to show that the saturation of the staves is certain in any event, so long as one side is in contact with water.

JAMES C. MEEM, Assoc. M. Am. Soc. C. E.—There are two points of weakness in the construction of stave pipe, which appear to have been met, and which are noted in the discussion, namely, the tendency to rot on the outside, and, in pipes of large diameters and made of thin staves, the tendency to distortion. Mr. Meem.

Some time ago the speaker, under C. H. Myers, M. Am. Soc. C. E., assisted in designing a 4-ft. sewer pipe intended to run under pressure. Comparative estimates as to the cost of cast-iron pipe and wood-stave, concrete-cased pipe were made.


½ IN. COATING OF PORTLAND CEMENT MORTAR, 1:2.
R. 2' 7¼"
R. 2' 1¼"
R. 2' 0"
SHOE.
48"
MILLED STAVE
CRADLE OF NATURAL CEMENT CONCRETE.
NATURAL CEMENT CONCRETE
½ IN. ROUND STEEL STRAP SPACED 2 FT. C. TO C.

DESIGN FOR 48 IN. CONCRETE-CASED WOOD-STAVE SEWER.

FIG. 5.

The cost of the former was found to be about $10.50 per foot, while the latter, to be built substantially as shown in Fig. 5, was estimated to cost about $5.75 per foot. Fig. 5 is a section of the

Mr. Meem. design, and would seem to overcome the two points of weakness noted. The shoe was substantially the same as that shown in Fig. 3, except that it was to have been made of cast iron. The rest of the design is self-explanatory.

Where the soil was soft or marshy, this sewer was to have been built on grillage, and, in that case, the design included a cradle of natural cement concrete conforming to the dotted lines shown in the figure, the cradle and concrete invert being, of course, merged into one. The cost of a sewer of this design on grillage of solid double rows of 2-in. planking at right angles was estimated to be about $8.00 per foot in this specific instance.

Unfortunately for experience this pipe has never been constructed, but it is believed that for certain purposes it would prove to be the most economic type of construction. The old City of New York has built a great deal of wood-stave sewer pipe; Brooklyn has also built several sewers of this material in the last two or three years, as it is especially well adapted to outfalls through crib-work and piers.

The speaker believes that these sewers have always been satisfactory, but he can only speak certainly of those in Brooklyn, and they have not yet been down long enough to give any indication as to their ultimate endurance. The tendency to rot is largely overcome by creosoting, and the tendency to distortion is prevented by making the staves quite thick.

Mr. Skinner. F. W. Skinner, M. Am. Soc. C. E.—Although the limits of economy of stave pipe and steel pipe are being contrasted, the speaker thinks there is some comparison between the economy of stave pipe and bored wooden pipe. He had occasion not very long ago to visit an establishment where bored wooden pipe is manufactured, and was quite impressed with the great economy of production. Large logs were turned to a suitable exterior diameter, and then the core was taken out so as to preserve the heart of the timber. The core was about 8 or 9 ins. in diameter, and sufficed for a smaller pipe, and was in turn counter-bored. The pipes were reinforced by the well-known method of winding, under tension, a spiral of thin flat metal around them. The ends were counter-bored slightly and connections made by inserting wooden thimbles. The process is extremely cheap as regards first cost, and for small lines under moderate pressures should give economical results.

CORRESPONDENCE.

HENRY B. PATTEN, M. Am. Soc. C. E.—The City of Cheyenne, Wyo., has built, altogether, under the Allen Patent, 10 259 ft. of stave pipe, as follows: Mr. Patten.

In 1888, 1 892 ft. of 30-in. pipe.
In 1889, 6 333 ft. of 30-in. pipe.
In 1889, 2 034 ft. of 20-in. pipe.

These pipes were planned as a conduit for water running under little or no head. A portion of the pipe was laid under circumstances such that it was only partly full of water during the greater portion of each year. As might have been expected, the portion so constructed decayed rapidly, and failed entirely in a few years.

Of the 30-in. pipe built in 1889, 2 000 ft. were replaced by vitrified earthenware pipe in 1896, after seven years' use. In 1897, 2 200 ft. more were replaced, having given only eight years' service. It is expected that it will soon be necessary to replace 2 133 ft. more of the 30-in. pipe, which is the remainder of the 30-in. pipe laid in 1889.

When the old pipe was removed, a considerable growth of grass roots was found inside. This is an impediment to the flow of water that should be considered as a partial offset to the tuberculation found in cast-iron pipe. It was also found that the pipe was distorted from the circular section. In some instances the cross-section was found to be quite elliptical, the original 30-in. circular pipe being found to be only 26 ins. in vertical diameter, while the horizontal diameter was nearly 34 ins.

In the writer's observation of the old pipe as it was removed, the following facts were noted:

First.—The decay of the pipe was greatest on the upper portion of the line where it carried the least water.

Second.—That pipe which had the least covering, and thus was nearest to the surface of the ground, was decayed the most.

Third.—The outside of the pipe, on the upper portion of its circumference, was decayed more than any other part of the pipe.

Fourth.—With old stave pipe, there may be, occasionally, a material resistance to the flow, due to the presence of grass roots which may have forced themselves through the moist staves or through the joints.

Fifth.—For the theoretically circular stave pipe, there is a possibility of distortion into an oval or elliptical cross-section, which will decrease the sectional area sufficiently to cause a diminution of the discharge.

F. W. D. HOLBROOK, M. Am. Soc. C. E.—At the eastern end of the Hoosac Tunnel, in 1865–1867, the air compressors, which furnished power for the drills, were operated by turbine wheels. The penstocks, Mr. Holbrook.

Mr. Holbrook. through which the water was conveyed from the canal to the wheels, were continuous wooden tubes, made of staves of variable length, with radial edges and concentric faces. The staves were held together by circular metal bands, spaced in accordance with the strains imposed. The penstocks were about 40 ft. long and about 5 ft. in diameter. Such construction was well known and in general use in western Massachusetts at that time, and therefore dates back to a much earlier period than is generally supposed.

Mr. LeConte. L. J. LE CONTE, M. Am. Soc. C. E.—The author is evidently strongly impressed with the special advantages of stave pipe, as compared with cast-iron and riveted pipe, within certain fixed limits.

The writer is quite willing to concede many of the important advantages claimed, provided the limit of pressure does not exceed 100 lbs. per square inch, as assumed in the paper. He takes exception, however, to the claim that the velocity coefficient c for stave pipe gradually increases with increase in diameter, and finally attains the extraordinary value of 163 for the 72-in. pipe. There is no proper authority for such a high value of c. With stave pipe, the highest value for c yet obtained by competent authority, and on a scale sufficiently large to inspire confidence, is about 143.

Of course, it is quite possible that future experience with larger pipes may develop higher values, but the Ogden experiments with the 72-in. pipe certainly do not furnish evidence upon which to base any hopes in this direction.

The writer strenuously objects to the palpably unfair consider ation given to riveted pipes in the paper. As pipe of this kind has been in constant use on the Pacific coast for the past thirty-five years, and on a very large scale, the writer is able to speak with confidence.

The life of any one of the three classes of pipe under consideration will depend chiefly upon the character of the soil in which it is buried. In ordinary soil, free from alkaline ground waters, riveted pipe, properly coated, will certainly last twenty-five years, as instanced to the writer's personal knowledge, by numerous examples. The following table from his memorandum book shows the life of some of the thinner grades of pipe:

Diameter, in inches.	B. W. G.	Year laid.	Year taken up.	Age, in years.	Head of water, in feet.
8	18	1874	1895	21	135
10	16	1865	1895	30	175
6	16	1873	1894	21	200
8	14	1865	1895	30	175
12	14	1868	1898	30	200
24	10	1872	1897	25	200

Mr. LeConte.

All these pipes were taken up, samples were taken and observations on the same duly recorded. The old pipes were then relaid under lighter pressures, and are now doing fairly good service.

Tuberculation is so rare on the Pacific coast that engineers, as a rule, give it little or no consideration in fixing the sizes of pipes. The waters being nearly always hard, the salts in time form a thin incrustation on the inner surface of the asphalt coating, and so far there has been no authentic case reported where c has materially diminished with the age of the pipe. Tuberculation is only troublesome where the waters are soft.

The writer particularly objects to the statements of comparative values of c in Tables Nos. 6 and 7. In Table No. 6 the value of the coefficient for clean steel-riveted pipe of all diameters and thicknesses is given as 111, which is clearly an error, and the coefficient for tuberculated 72-in. riveted pipe is given as 89, or the same as that for a tuberculated 20-in. cast-iron pipe. Comment is unnecessary.

It therefore follows that Table No. 7, giving the relative discharging capacities, is equally objectionable. The tables of comparative cost (Nos. 8 and 9) are replete with comparisons unfair to riveted pipe. For example, take the 30-in. pipe at San Francisco, Table No. 9. The cost of stave pipe, 30 ins. in diameter, capable of sustaining a 200-ft. head of water (a limit of comparison of the author's own selection), is given as \$2.23 per lineal foot; while the cost of $\frac{3}{8}$-in. riveted pipe 30 ins. in diameter, capable of sustaining a 200-ft. head of water, is given as \$3.79 per lineal foot. The author omits to mention the important fact that this $\frac{3}{8}$-in. double-riveted pipe will safely stand a 900-ft. head of water.

$$P = \frac{16\,000 \times t}{r}, \text{ or } P = \frac{16\,000 \times \frac{3}{8}}{15} = 400 \text{ lbs.} = 900 \text{ ft.},$$

in which P = the pressure in pounds per square inch,

t = the thickness of the shell in inches,

and r = the radius of the pipe in inches. The author, therefore, has, in this 30-in. pipe, four times the amount of steel that the case calls for—and so on through the whole table.

The strong points in favor of riveted pipe are economy in first cost, and durability—it lasts at least twenty-five years. In California, engineers have never claimed a high value for c for riveted pipe, as compared with cast-iron pipe of the same diameter. The value of c for large sizes is found to range from 115 to 120, and for small sizes from 100 to 110. These values are further modified by the percentage of heavy plate iron there may be in the pipe line. This factor makes the determination of the correct value of c, for any proposed pipe line, a very complex problem, so much so that it has become a maxim, so to speak, that every riveted pipe line has its own peculiar coefficient.

Theoretically, the stave pipe should certainly develop a high value

Mr. LeConte. for c, but this class of pipe has been in use only eight years, and there is much yet to be learned about it.

The sphere of its usefulness is so limited in extent that its economic application will be confined almost entirely to special cases where the pressures are low. For all higher pressures riveted and lap-welded pipes are the only kinds which are fit for the services they are called upon to perform.

Mr. Henny. D. C. HENNY, M. Am. Soc. C. E.—The author has distinguished three distinct sources of strain in the band of a stave pipe, and the formulas for the determination of this strain express the effect of each source separately, $P f R$ being the strain from water pressure, $X = \frac{3}{2} P f t$ the strain from cinching, and $E'' t f$ the strain caused by the swelling of the wood, all of which are added together to establish a value for S, the least permanent band strain in a tight pipe, as in the author's formula (1).

The writer cannot admit the correctness of this reasoning, because the interdependence of these strains, to which attention has been directed by the author himself on page 29, precludes the determination of the final strain by simple addition. Nor has the author made fully clear what was meant by X, whether the strain in the band immediately after back-cinching, or immediately before the pipe is filled with water, or whether it represents some remaining influence in the final strain of the cinching of the band. In any case there is no evidence why it should be in any way dependent on the water pressure P, and the value assigned to X by the author seems to be purely arbitrary.

The writer believes it to be self-evident that when there is no pressure on the pipe the strain in the band is balanced by the compressive lateral strain in the staves. Clearly, assuming the staves to have no compressive strength whatever, no amount of cinching could produce any strain in the band. When there is water pressure on the pipe, the lateral strain in the wood must balance all the excess in the band strain over that due to water pressure, otherwise motion would ensue until a balance is established.

Calling y the average compressive lateral strain in the staves per square inch of compressed section when the pipe is under a pressure P, then

$$S = P f R + f t y \ldots\ldots\ldots\ldots\ldots\ldots \quad (a)$$

The author is correct in reasoning that the ultimate swelling force of wood is the measure of its ultimate resisting force when saturated, hence the maximum permanent value of y is E'' and

$$S_{max} = P f R + f t E'' \leqq (R + t) E \ldots\ldots\ldots\ldots \quad (b)$$

TABLE No. 10.—STRAINS IN BANDS ON 10-IN. REDWOOD STAVE PIPE, Mr. Henny. IN POUNDS.

Date.	Gauge Readings in Pounds.								
	0	5	10	15	20	30	40	50	60
Bands: 10 ins. center to center.									
Jan. 31st, 1896.	4 300	.....	.....	.....	.....	.....	.....	.....	.....
" 31st, 1896.	3 700	3 800	3 850	3 925	4 100	.....	.....	.....	.....
Feb. 1st, 1896.	2 600	.....	.....	.....	.....	.....	.....	.....	.....
" 3d, 1896.	2 300	.....	2 500	.....	.....	.....	.....	.....	.....
" 4th, 1896.	.....	2 150	.....	.....	.....	.....	.....	.....	.....
" 5th, 1896.	.....	2 100	.....	.....	.....	.....	.....	.....	.....
" 6th, 1896.	.....	2 100	2 250	.....	.....	.....	.....	.....	.....
" 10th, 1896.	1 900	.....	2 075	.....	.....	.....	.....	.....	.....
" 11th, 1896.	.....	.....	2 075	.....	.....	.....	.....	.....	.....
" 13th, 1896.	.....	.....	2 050	.....	.....	.....	.....	.....	.....
" 15th, 1896.	.....	.....	2 075	.....	.....	.....	.....	.....	.....
" 17th, 1896.	.....	.....	2 075	.....	.....	.....	.....	.....	.....
" 19th, 1896.	.....	.....	2 000	.....	.....	.....	.....	.....	.....
" 20th, 1896.	.....	.....	2 000	.....	.....	.....	.....	.....	.....
" 21st, 1896.	.....	.....	2 000	.....	.....	.....	.....	.....	.....
" 24th, 1896.	.....	1 750	2 000	.....	.....	.....	.....	.....	.....
" 27th, 1896.	1 775	1 800	.....	.....	2 200	.....	.....	.....	.....
" 28th, 1896.	.....	.....	.....	2 000	.....	.....	.....	.....	.....
" 29th, 1896.	1 750	.....	.....	.....	.....	.....	.....	.....	.....
Mar. 2d, 1896.	1 750	1 800	.....	2 000	.....	.....	.....	.....	.....
" 3d, 1896.	.....	.....	.....	2 000	.....	.....	.....	.....	.....
" 4th, 1896.	.....	.....	1 950	.....	.....	.....	.....	.....	.....
" 5th, 1896.	1 750	.....	.....	.....	2 200	.....	.....	.....	.....
Bands: 5 ins. center to center.									
" 5th, 1896.	1 500	170	.....	.....	1 700	1 800	1 950	.....	2 350
" 6th, 1896.	1 650	.....	.....	.....	.....	.....	.....	.....	.....
" 7th, 1896.	1 600	.....	.....	.....	.....	.....	.....	.....	.....
" 9th, 1896.	.....	.....	.....	.....	.....	.....	2 000	.....	.....
" 10th, 1896.	.....	.....	.....	.....	.....	.....	2 000	.....	.....
" 11th, 1896.	1 475	.....	.....	.....	.....	.....	1 975	.....	.....
" 12th, 1896.	1 475	.....	.....	.....	1 700	1 800	2 000	.....	.....
" 13th, 1896.	.....	.....	.....	.....	.....	.....	2 000	.....	.....
" 14th, 1896.	1 475	.....	.....	.....	.....	.....	2 000	2 150	2 300

This maximum strain can be attained only by re-cinching after the pipe has become filled and is under pressure, which is rarely, if ever, done in practice. In case the pipe is cinched up to the limit, the strain in the band may be $f\,t\,E''$ before filling. When pressure comes on, the staves will be forced outward, owing to the compression of the wood immediately under the bands, and to deflection between the bands, to which the author has duly called attention. While its motion is small it lessens materially the lateral compression of the staves, and relieves to that extent the portion of the band strain due to stave compression. The extent of relief being unknown, it would not be practicable to take cognizance of it in the determination of maximum strains, but so far as formula (*a*) is concerned it may be stated that as P becomes larger for any given pipe, y becomes smaller until finally leakage results.

An experiment made by the writer some three years ago may be of interest here as illustrating the dependence of stave compression on water pressure, although it was originally undertaken to determine

Mr. Henny

the safe maximum spacing for pipe with thin staves, and to inquire into the degree to which it would be desirable or imperative to carry the rather expensive process of cinching.

A section of 10-in. pipe about 8 ft. long was built of redwood staves $1\frac{1}{16}$ ins. thick, and having $\frac{3}{8}$-in. round steel bands with cold-pressed threads. Upon test these bands showed a tensile strength at the elastic limit of from 4 100 to 5 600 lbs. and a breaking strength of from 6 900 to 7 300 lbs. The bands were thoroughly cinched, and heads were placed over the ends of the section and connected by longitudinal bolts. One of the bands was provided with the strain-measuring device described and illustrated in a previous paper by the author.* Fig. 1, Plate I, of that paper shows the device in position on the test pipe.

The first experiment was with bands spaced at 10 ins. from center to center, and lasted 35 days, during which time pressure was kept on the pipe up to 20 lbs. per square inch. The second experiment, with bands 5 ins. apart, lasted 9 days, and the pipe was subjected to pressures up to 64 lbs. per square inch.

The actual band strain is recorded in Table No. 10.

Upon the basis of band strains at the end of each experiment for various gauge readings the analysis given in Table No. 11, shows the strains in the band and in the staves.

TABLE No. 11.—STRAINS IN 10-IN. REDWOOD STAVE PIPE UNDER PRESSURE, IN POUNDS.

Gauge reading. P.	Band Strain. Total measured. S.	Band Strain. From water pressure. $P f R$.	Band Strain. From stave compression. $f t y$.	Average lateral compression of staves per square inch. y.	Pressure of band on stave per lineal inch.
Bands: 10 ins., center to center.					
0	1 750	0	1 750	165	285
5	1 800	253	1 547	146	293
10	1 950	506	1 444	136	318
15	2 000	759	1 241	117	326
20	2 200	1 012	1 188	112	359
Bands: 5 ins., center to center.					
0	1 475	0	1 475	277	241
20	1 700	506	1 194	224	277
30	1 800	759	1 041	196	294
40	2 000	1 012	988	186	326
50	2 150	1 265	885	166	351
60	2 300	1 518	782	147	375

NOTE.—Actual diameter, 10.13 ins. Bands were cinched very hard. Some fibers on bastard staves had snapped. Crease made by band measured from $\frac{1}{16}$ to $\frac{1}{4}$ in.

Tables Nos. 10 and 11 show some interesting facts in relation to lateral stave compression for different spacing of bands, to which ref-

* "The Astoria City Water-Works," *Transactions*, Am. Soc. C. E., Vol. xxxvii, p. 1.

erence will be made hereafter. For the present it is sufficient to note the decrease of band strains from stave compression, $f t y$, with the increase of water pressure. Mr. Henny.

The maximum band strain as expressed by formula (b) is greater than that required for tight pipe. When, on a pipe under pressure, the strain in a band is released by turning the nut, the compressive strain in the staves will be decreased, until finally, leakage in the seam joints results, commencing half way between the bands, where the compressive strain is least. Calling the stave compression half way between the bands y_1, and that at the bands y_2, the average stave compression y will be approximately $\frac{y_1 + y_2}{2}$, and the condition of tightness will be expressed by $y_1 > P$.

Where the spacing of the bands is not wide, and where the staves are not unusually thin (conditions referred to hereafter) y_2 will generally be but little greater than y_1, and consequently $y_1 + y_2$ will be little greater than $2\,y_1$, and, with the exceptions noted, it is believed that tightness is generally insured by the condition $y_1 + y_2 = 3\,P$ or $y = \frac{3}{2}P$. Substituting in formula (a) there results for the least band strain in tight pipe:

$$S = P f R + f t \frac{3}{2} P$$

which should be equal to the safe tensile strain in the band; hence

$$s = P f \left(R + \frac{3}{2} t\right)$$

So far as indentation under the band is concerned, the safe bearing power under the band should not be exceeded by the safe band strain; therefore

$$s = P f \left(R + \frac{3}{2} t\right) \leq \left(R + t\right) e \quad \ldots\ldots \quad \ldots\ldots\ldots (c)$$

from which the spacing

$$f = \frac{s}{P \left(R + \frac{3}{2} t\right)} \leq \frac{\left(R + t\right) e}{P \left(R + \frac{3}{2} t\right)} \ldots\ldots\ldots\ldots\ldots (d)$$

Some stave-pipe specifications have required that the greatest strain in the band should fall within the limit of elasticity of the steel, so that no permanent elongation may result from either excessive cinching or from subsequent swelling and pressure strains. This condition is generally complied with, under ordinary proportions of pipe design, and usually the wood in the staves will commence to fail under the cinching strain long before the elastic limit in the band is reached. In extreme cases, however, of wide spacing, large diameter,

Mr. Henny. very dry lumber, hard cinching and quick filling and putting under pressure of the pipe, the elastic limit may be temporarily passed, but the writer can discover no special harm in this, since the soaking of the wood would quickly release the excessive strain. It is for this reason also that in the above formulas no reference has been made to temporary strains and because with stave pipe built of staves and bands of ordinary proportions, with the proper kind of lumber, there is no danger that the temporary band strains will approach too closely to the breaking point.

Formula (*d*) has been used by the writer for many years to determine the spacing of pipe bands, and he sees no reason to deviate from this practice. It should be remembered, however, that the formula is based upon the assumption that the difference between the compressive strain in the wood at the band and that between the bands is not great, an assumption that is not safe when the spacing is wide or the staves are thin. The exact effect of the deflection of the staves between the bands is exceedingly difficult to determine, and as a practical solution of this question the writer has generally fixed upon some maximum spacing which practice and experiments have shown to be safe.

For staves run from 2-in. lumber the maximum spacing has generally been made 12 ins., which has been reduced, however, to 11 and 10 ins. as the diameter of the pipe increased, without a corresponding increase in the stave thickness, in order to give to the pipe the rigidity required to resist deformation and to support top loads.

For staves run from 1½-in. lumber the maximum spacing has been fixed at 10 ins., because the staves deflect more easily, and consequently there is a greater difference in the compressive strains at points between the bands and under the bands. Thus, for light heads the spacing is made closer than would result from the use of formula (*d*), nor is the reduction of spacing confined to pressures below the limit for which formula (*d*) indicates the assumed maximum spacing to be sufficient, but the reduction is graduated over higher pressures as well, up to some point, the selection of which must be largely a matter of judgment and experience.

If the reasoning on which formula (*d*) is based be correct, exception must be taken to the author's determination of the factors of safety in the bands of existing pipe lines as given in Table No. 5.

The column "Resulting factor in band, including all strains," would show different values, as the total band strain upon which it is based would be determined by the addition of strain from water pressure and strain from swelling staves, without the further addition of an assumed strain resulting from cinching. The writer does not wish to imply, however, that the values found by the author for resulting band factors are in themselves too low. While it is held that no addition should have been made for cinching strain, it is quite possible

that the swelling force E'' may at times be higher than 100 lbs., as assumed by the author. Mr. Henny.

To determine actual factors in existing pipe lines by means of formulas alone is considered impracticable, because the compression of the staves in the pipe, when saturated and under pressure, varies with the degree of cinching of the bands and the dryness of the staves at the time of construction. These are generally unknown or at least very uncertain, and even were they known, their exact effect on final stave compression would still be in doubt. It may be assumed that the author gave probable rather than either actual or minimum factors, and, if so, the writer believes that the assumption $E'' = 100$ lbs. is sufficiently high; but that, as stated, the supposed strains resulting from cinching, given in Table No. 5, should have been omitted in the determination of probable total band strains.

It is evident that any change in the total band strains would effect corresponding changes in the computed band pressures on the staves as given in the last two columns of Table No. 5.

It will be observed that formula (d), contains but one coefficient to be determined by experiment, namely "e," the resistance the staves offer to indentation by the bands.

The necessity for its determination was promptly realized by the writer, and he, so far as facilities at hand would permit, conducted some simple experiments with redwood. Rods of various diameters were laid on the flat side of dressed samples, the position of the rod being in each case perpendicular to the direction of the fiber. The test pieces were $1\frac{1}{16}$ ins. thick and $5\frac{1}{16}$ ins. wide, dressed on four sides. Edge-grain, diagonal-grain and bastard-grain samples were selected. One set had been kiln-dried and averaged 1.67 lbs. per lineal foot in weight, while another set had been submerged in water for ten days and showed an average weight of 2.10 lbs. per lineal foot.

After each sample had been placed in position and the rod had been laid upon it, a load was applied by means of a weighted lever, the weight being slowly increased and the width of the bearing measured, until the first evidences of cracking wood fibers appeared.

Table No. 12 gives the greatest load and corresponding width of bearing before damage to the wood resulted.

The writer fully realizes that wood, even of the same tree, is a very variable material, and that experiments made on single samples can have no far-reaching importance. The results are believed, however, to be not devoid of interest and to warrant some general conclusions.

It will be noted that the width of bearing surface generally approximates closely to the radius of the rod before injury to the wood results, as has been assumed by the author. It will further be observed that the direction of the annular rings has a decided influence on the bearing power, the edge grain sustaining 60 to 100% greater loads than

Mr. Henny

TABLE No. 12.—Width of Bearing, Load per Lineal Inch and Load per Square Inch of Bearing Surface of Round Rods laid on Clear Redwood, Perpendicular to the Direction of the Fiber.

Diameter of rod, in inches.	Edge Grain.		Diagonal Grain.		Bastard Grain.		
	Dry.	Wet.	Dry.	Wet.	Dry.	Wet.	
¼	5/32	5/32	.....	3 1/32	5/32	5/32	Width of bearing, in inches.
	317	277	.....	286	179	179	Pounds per lineal inch.
	2 028	2 216	.....	2 614	1 432	1 145	" square "
⅜	7/32	7/32	6/32	6/32	6/32	5 1/32	Width of bearing, in inches.
	415	415	317	317	180	228	Pounds per lineal inch.
	2 213	1 897	1 674	1 674	1 152	1 398	" square "
½	9/32	8/32	8/32	8/32	8/32	7/32	Width of bearing, in inches.
	513	415	415	461	267	228	Pounds per lineal inch.
	2 052	1 660	1 660	1 844	1 068	1 042	" square "
⅝	10/32	10/32	10/32	9/32	9/32	11/32	Width of bearing, in inches.
	510	510	460	448	317	400	Pounds per lineal inch.
	1 632	1 632	1 472	1 792	1 127	1 172	" square "
¾	11/32	10/32	12/32	10/32	12/32	12/32	Width of bearing, in inches.
	558	558	508	460	415	415	Pound per lineal inch.
	1 785	1 785	1 354	1 635	1 106	1 106	" square "
⅞	14/32	13/32	13/32	14/32	14/32	14/32	Width of bearing, in inches.
	701	701	603	603	415	458	Pounds per lineal inch.
	1 602	1 602	1 286	1 380	948	1 046	" square "

the bastard grain, the diagonal grain giving intermediate values. This was not entirely unexpected. Redwood, like most soft woods, consists of alternate hard dark rings (summer wood) and soft light-colored rings (spring wood). In edge grain the rod is supported by the upper edges of a large number of hard rings, while in bastard grain it lies flat on one of these rings, which receives its own support from a soft ring underneath, and is easily pressed down and broken.

Another interesting fact disclosed by the experiments is that the sustaining power per square inch grows smaller as the diameter of the rod increases. An explanation of this may, perhaps, be found in the fact that the indentation from a round rod produces not only downward compression, but also a stretching of the upper fibers in which the rod lies suspended, as it were, and the supporting effect of these stretched fibers must be proportionately greater for narrow than for wide rods.

Finally, the rather curious fact is developed that wood, when becoming saturated, does not seem to lose in bearing power. The fiber when wet does not break and snap off readily, which permits more deformation without injury, and such increased deformation does not necessarily result in a greater width of actual contact.

While generally the loads were borne for only a short time, they were sometimes left on for several hours or throughout the night, yet no further marked settlement appeared to occur. The writer, therefore, concludes that, contrary to the assumption of the author, there is no great difference between the temporary and the permanent sustaining power, E' and E.

Mr. Henny.

The supporting power of saturated redwood for a $\frac{3}{8}$-in. rod was found to vary from 415 to 228 lbs. per lineal inch of rod, according to the grain of the wood, while the 10-in. pipe experiments previously noted (Table No. 11) gave a maximum of 375 lbs.; by which pressure, however, the fibers of the bastard-grain staves had been injured and the bearing increased to a width greater than the radius of the rod.

Comparing the results of the experiments with the value of E, assumed by the author, on page 38, it is found that the assumption $E = 240$ lbs. for $\frac{1}{2}$-in. bands is about correct for bastard grain. As to the safe bearing power, e, the writer believes that the experiments indicate sufficiently that the value to be given to it for the various diameters of bands should not be based on a uniform safe pressure per square inch of contact, but that it should decrease with an increase of diameter, and he has generally based the spacing on Table No. 13, deduced from the above experiments.

TABLE No. 13.—Assumed Safe Loads of Round Bands on Clear Redwood Staves.

Diameter of band, in inches.	Width of bearing, in inches.	Safe Load, in Pounds.	
		Per square inch.	Per lineal inch.
$\frac{3}{8}$	$\frac{3}{16}$	747	140
$\frac{1}{2}$	$\frac{1}{4}$	700	153
$\frac{5}{8}$	$\frac{5}{16}$	660	165
$\frac{3}{4}$	$\frac{3}{8}$	640	200
$\frac{7}{8}$	$\frac{7}{16}$	620	232
1	$\frac{1}{2}$	600	262

If it be desired to determine the maximum strain that resistance to indentation enables the staves to transmit to the bands, values for E, equivalent to from 2 200 to 1 600 lbs. per square inch of band contact should be used.

The swelling force and the lateral compressive strength of the wood E'', ordinarily need not be considered in the determination of band spacing, for reasons previously stated (which do not apply to the design of tanks, owing to greatly different proportions and conditions). They should, however, receive careful consideration in ascertaining the limits of pressure for stave pipe and in deciding upon the methods to be followed in construction, especially in regard to the extent to which back-cinching should be carried to insure a tight pipe. The writer has made a series of experiments to determine the value of E'' for redwood and for Oregon fir, which show widely varying results, partly due, no doubt, to differences in the wood itself, and partly to the difficulty of securing an equal degree of dryness for all the samples when put under test.

Mr. Henny. The test pieces were generally from 10 to 12 ins. in length, and they were compressed in the direction of their width, which was about $5\frac{1}{2}$ ins. The thickness varied from $1\frac{1}{2}$ to $2\frac{1}{2}$ ins. The test pieces were placed between two 1-in. iron plates, each provided with a hole corresponding to a hole bored through the sample in an exactly central position. A $\frac{5}{8}$-in. bolt was passed through the hole, and upon the projected thread was placed the measuring device previously mentioned. The pieces had been kiln-dried and had been kept in a dry place ready for use, but it is very probable that some moisture had been reabsorbed. The bolt was usually tightened until a strain of from 4 500 to 7 000 lbs. was reached, and then the test piece was submerged in water either with the original strain left on the bolt or after the strain had been released to about 1 000 lbs. or less. The strains were read from day to day until there seemed to be no further change, when the sample was taken out; or it was put back in the water with the strain increased or released by turning the nut; or it was placed in dry air, as indicated in Tables 14 and 15. It should be stated that the maximum movement permitted by the spring of the measuring device was 0.02 in. for a 10 000-lb. load.

TABLE No. 14.—Changes of Compressive Strain in Clear Redwood when Becoming Saturated.

Number of test pieces.	Direction of grain.	General dimensions, in inches.	Pressure in wood per square inch of compressed section, in pounds.	Weight per foot B. M., in pounds.		Remarks.
				Before experiment.	After experiment.	
27	Edge.	$2\frac{1}{2} \times 12$	50- 77 (20) 171-187 (15)	2.14	3.04	
28	"	$2\frac{1}{2} \times 12$	27- 60 (17) 30- 40 (12)	2.12	3.25	
29	"	$2\frac{1}{2} \times 12$	197-184 (21)	2.16	3.01	
9	"	$1\frac{1}{2} \times 10$	491-161 (27)	2.16	3.09	
10	"	$1\frac{1}{2} \times 10$	44-161 (15)	2.14	3.02	
11	"	$1\frac{1}{2} \times 10$	471-175 (32) 31-104 (17)	2.13	3.30	Grain had slipped slightly
4	"	$1\frac{1}{2} \times 12$	28- 53 (18) 140-112 (12)	1.88	3.33	
8	Diagonal.	$2\frac{1}{2} \times 12$	24- 78 (14) 217-131 (14) 239-141 (22) 254-154 (24)	1.75	2.21	
12	"	$1\frac{1}{2} \times 10$	74-108 (14)	2.50	3.38	Had been cinched to 471 before release and submersion, and grain had slipped.
13	"	$1\frac{1}{2} \times 10$	363-144 (21)	2.47	3.29	
15	Bastard.	$1\frac{1}{2} \times 10$	51-116 (21)	1.64	2.25	
16	"	$1\frac{1}{2} \times 10$	348-191 (18)	1.75	2.79	
17	"	$1\frac{1}{2} \times 10$	333-167 (21)	1.71	3.29	
10-in. test pipe.	.....	$1\frac{1}{16} \times 10$	404-245 (1) 245-165 (33)			
10 " "	.....	$1\frac{1}{16} \times 5$	282-277 (9)			

Note.—Numbers in parentheses indicate duration of each experiment in days.

TABLE No. 15.—CHANGES OF COMPRESSIVE STRAIN IN CLEAR OREGON FIR WHEN BECOMING SATURATED AND WHEN DRYING. Mr. Henny.

Number of test piece.	Direction of grain.	General dimensions, in inches.	Pressure in wood per square inch of compressed section in pounds.	Weight per foot B. M., in Pounds.		Remarks.
				Before experiment.	After experiment.	
18	Edge.	1½ × 10	[511–306] (17) 306–122 (40)	2.80	3.80	Between first and second experiments test piece was placed alternately in air and water, and with each release of pressure from drying, bolt was reincched.
19	"	1½ × 10	51–183 (14) 75–122 (9)	2.77	3.72	
20	"	1½ × 10	136–163 (8) 88–156 (2) [156– 90] (20)	2.81	2.75	
2	Diagonal.	2½ × 10	7– 74 (16) 13– 34 (12)	....	.....	
6	"	1½ × 12	28– 92 (9) 274–129 (19) 291–151 (25)	....	....	Test piece had buckled, showing a deflection of 0.07 in. in the center.
21	"	1½ × 10	122– 88 (10) [88– 34] (5) [142– 34] (8) 34– 88 (13)	2.85	3.45	
22	"	1½ × 10	54– 68 (9) 156– 99 (7) 150– 99 (6)	2.67	2.82	Test piece had buckled, showing a deflection of 0.02 in. in the center.
23	"	1½ × 10	68– 75 (7)	3.01	3.27	
24	Bastard.	1½ × 10	68–238 (14) 61–171 12)	3.25	3.82	Test piece had buckled, showing a deflection of 0.06 in. in the center.
25	"	1½ × 10	284–329 (5) 98–295 (7) [295– 13] (15) [123– 34] (6)	2.99	3.01	
26	"	1½ × 10	148–269 (14)	2.97	3.79	Same as test piece 20.
18-in. test pipe.	.....	1⅜ × 12	288–153 (13) 7– 94 (17)	2.53	3.90	
18 " "	.....	1⅜ × 12	30– 74 (19) 33–121 (8) 121– 97 (23)	3.10	4.20	

NOTE.—Numbers in parentheses () indicate duration of each experiment in days. Figures in brackets [] show changes of pressure in dry air; all other figures are for test piece submerged in water.

There are many interesting deductions to be made from these experiments. The writer will confine himself to the following:

Bastard grain shows a decidedly greater swelling power and compressive strength than either edge grain or diagonal grain, which renders the selection of bastard grain staves very desirable for the high pressure portions of a pipe line, affording a further advantage in offering a greater safeguard against percolation. It will also be noted that after the first swelling strain had been released, the further strain from swelling never reached the original value and generally remained considerably below it. This emphazises the necessity of hard-cinching the bands on pipes built with staves that are not perfectly dry, a condition rarely attained.

Mr. Henny. Another interesting point brought out in the tests with fir is that repeated wetting and drying will necessitate repeated screwing up of the bolt to prevent the entire release of the pressure, but that finally a point is reached when drying out may reduce the strain, but can no longer cause complete release, which is of importance rather in tank than in pipe construction.

The tests with 10-in. redwood pipe described by the writer, and those with 18-in. Oregon fir pipe, mentioned by the author, have both been included in the tables, for convenient comparison. In regard to the former some further remarks may not be out of place.

The band on the pipe with 10-in. spacing had originally been screwed up to a tension of 4 300 lbs. (stave compression per square inch, 404 lbs.; band pressure per lineal inch, 702 lbs.). This fell in one day to 2 600 lbs. (stave compression per square inch, 245 lbs.; band pressure per lineal inch, 425 lbs.), evidently as a result of a yielding of the staves in width as well as under the band. This strain, in the course of twenty-nine days, was further reduced to 1 750 lbs. (stave compression per square inch, 165 lbs.; band pressure per lineal inch, 285 lbs.) where it remained. As with water pressure on the pipe the band pressure per lineal inch increased to 375 lbs. without yielding, it is apparent that the final reduction in lateral compression of the staves was not due to a yielding of the wood under the band, but solely to lack of compressive lateral strength.

Upon the termination of the experiments on the pipe with 10-in. band spacing it might have been concluded that 165 lbs. per square inch was the permanent compressive strength of the saturated staves. Yet when the band spacing was reduced to 5 ins. the same staves sustained a compression load of 282 lbs. per square inch, which load suffered practically no reduction during the nine days that the test lasted.

Experiments, few in number, with different samples of redwood, under varying conditions, may not offer sufficient basis for scientific deductions, still the writer is strongly drawn to the conclusion that the greater compressive strength of staves in pipe with 5-in. band spacing, as compared with that of staves in pipe with 10-in. band spacing, and of the latter as compared with that of the average of straight test pieces, may well result from the side support, which the staves receive from the surrounding bands, against folding and buckling, which was frequently observed in unsupported test samples.

The economy in the use of oval bands on small pipe, as a means of securing the required bearing surface, was fully pointed out by the author. The difference in cost per pound, between oval and round bands, as quoted by the mills, is unfortunately not as trifling as was assumed, although in general the writer can agree with the author's table No. 4, giving economic proportions for pipe design. He has,

however, often used $\frac{3}{8}$-in. round bands in preference to oval bands on pipe lines smaller than 22 ins. diameter, in case the pressures generally were light, because up to a certain pressure the same number of round bands as of oval bands will suffice, the spacing not being governed by limited bearing surface, but by possible stave deflection between bands. Up to that pressure the use of round bands will therefore be more economical, and when the higher pressure is reached, where the cost of round and oval bands would be the same, the writer prefers the use of the former, as a greater weight of steel is obtained, causing a corresponding increase in the probable life of the pipe without extra expense. If, on such a pipe line, scattered short stretches occur, where, so far as purchase-price of material is concerned, there would be economy in using oval bands, it remains an objection, from the practical point of view of a pipe builder, to make frequent changes for short distances from the one to the other kind of bands. The author's argument applies, however, with full force to pipe lines where the pressure generally is high. Mr. Henny.

The alleged disadvantage of oval bands, in exposing a greater surface to corrosive action than round bands, is more apparent than real, at least so far as the adopted sizes are concerned, since a $\frac{5}{16}$ x $\frac{7}{16}$-in. oval band has a surface exceeding that of a $\frac{3}{8}$-in. round band by only 1.3 per cent.

An important subject in connection with stave pipe, which the author has not touched, deserves attention. Reference is made to the possibility of leakage, which, in view of the relatively large number of seam and butt joints, might well predispose those who have had no experience with it against stave pipe. The author has mentioned this matter in his paper on the Astoria Water-Works,* where a test of tightness of some three miles of 18-in. stave pipe was described. It is believed that he has lately made some additional measurements on this subject, a statement of which would undoubtedly add to the value of the paper.

JAMES D. SCHUYLER, M. Am. Soc. C. E.—This paper will be accepted by the friends and advocates of wood stave pipe as the most systematic and logical analysis of the subject that has yet been attempted, and the author is certainly entitled to the gratitude of the profession for the very clear and concise statements of the conclusions to be drawn from the lessons of experience with this class of pipe up to the present day. Mr. Schuyler.

Reference has been made to the experiments on the carrying capacity of the 30-in. line, 16.4 miles long, supplying the City of Denver, which were conducted, in 1892, under the supervision of the writer. Unfortunately, he has not at hand the notes of these experiments in detail, although they may still be found among the records of the

* *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 1.

Mr. Schuyler. Water Company. In brief, they consisted of a careful notation of the time of filling a measured depth in the reservoir at the lower end of the line, all outlets being carefully closed while the experiments were in progress. They extended over a period of more than twelve hours, and were checked at frequent intervals by current-meter observations, at one of the manholes, where the pipe was near the hydraulic grade line. The result of the experiments gave the value of the coefficient n in Kutter's formula as somewhat less than 0.10, a number of computations having been made of progressive measurements during the progress of the filling of the reservoir, within the time stated. These computations gave slightly varying results, for the reason that the pipe did not discharge freely at the top of the reservoir, but entered it at the bottom, and, as the water rose, the hydraulic gradient was constantly changing and lessening the velocity in the pipe. The experiment, as a determination of the capacity of a wood stave pipe *per se*, was further complicated by the fact that the total length of the conduit was not of the same material, but, in addition to the 87 580 ft. of wood pipe, there was, near the lower end, 17 145 ft. of 30-in. cast-iron pipe, as a portion of the line involved in the test, and also a cement-lined, circular tunnel, 36 ins. in diameter and 2 288 ft. in length. For these reasons, a definite determination of frictional coefficients, applicable to the wood portion of the conduit, was not possible, although the results appeared to justify the conclusion drawn in a former paper,* that the coefficient n of Kutter's formula was, in this case, as low as 0.096 for the wood pipe. In deriving this inference it was necessary to apply to the cast-iron portion such mean coefficients as experience with that class of pipe seemed to warrant, and a mean of a number of experiments published in Trautwine and Hering's translation of Ganguillet and Kutter's work was used.

Mr. Adams. ARTHUR L. ADAMS, M. Am. Soc. C. E.—The discussions and correspondence present much that will be of substantial value in reaching ultimate conclusions regarding the questions to which the paper gives rise. The new data presented, particularly so far as they relate to the determination of probable strains, are most valuable, and in some respects would seem to warrant some change in the author's assumptions, though it is believed without influencing the final results very much. Many of the objections taken to the author's statements have, on the other hand, arisen from an imperfect perusal of the paper, a failure to grasp the measure of its intended scope, and, to some extent, from a very imperfect knowledge of the subject treated.

Mr. Henny has contributed a most interesting discussion, the subject being one on which he is remarkably well qualified, by experience, thought and experiment, to speak. The tables of experimental results are interesting, and constitute a substantial addition to existing knowl-

* *Transactions*, Am. Soc. C. E., Vol. xxxi, p. 144.

edge of a subject at best not much investigated. He contends with much clearness and force in favor of the use, under all conditions, of the formulas designated by the author as (*C*) and (*D*) for the determination of band spacings, instead of formulas (*A*) and (*B*), claiming that the sum of all strains transmitted to the bands, additional to that resulting from water pressure, cannot be determined by the summation of the same. The author is disposed to believe this point well taken, as set forth in the formula (*b*), but the results of further experimentation to determine the amount of swelling strain, which he submits, would seem to indicate as advisable the assumption for E'' of a figure considerably greater than the 100 lbs. per square inch suggested by the author; and since the maximum pressure suitable for stave-pipe constructions is not greater than this, while the average pressure, in its economic field of usefulness, is very much less, it would seem that the factor, $E'' t f$, would always predominate in the production of band strain rather than the $P f \frac{3}{2} t$. The formula, $S = P f (R + \frac{3}{4} t)$, gives the band strain in a pipe which is just free from seam leakage and little more. This is the minimum permissible, and not the strain probably prevailing. The author can scarcely agree with the contention that: Mr. Adams.

"When pressure comes on, the staves will be forced outward, owing to the compression of the wood immediately under the bands, * * *. While this motion is small it lessens materially the lateral compression of the staves, * * *."

Redwood shrinks transversely in drying about 4 per cent. So long as the proportions are restrained much below that originally prevailing, it must be capable of exerting pressure. An increase of even 1% in the width of the staves by swelling would cause an increase of 1.03 ins. in the diameter of a 30-in. pipe, thus necessitating the further sinking of the bands $\frac{1}{2}$ in. into the staves, if the strain from this source is to be thus materially lessened. If, therefore, either factor is to be omitted from the formulas, in deference to the first contention, it should, as previously stated, be X, or its assumed equivalent $P f \frac{3}{2} t$, rather than $E'' t f$. Such a modification, with some such increase in value to be assigned to E'' as the latter experiments seem to warrant, will not materially affect the results set forth in the table of probable strains prevailing in different pipe lines.

In structural work, a suitable factor of safety is a provision against failure from more or less unavoidable defects in material, from strains abnormal or indeterminable, originating from within or without the structure, and against undue termination of life from deterioration. The author does not think that a proper regard for these requirements will ever warrant the designing of a pipe along lines anticipating the straining of the materials even temporarily beyond the elastic limit; and he believes that he has already shown that, at least in pipes of any considerable size, the yielding of the wood beneath the bands cannot be counted on to afford much release of the strain from swelling timber.

Mr. Adams. The differences in bearing power of the staves, per unit of contact for bands of different diameters, as experimentally determined, are certainly worthy of careful consideration.

Regarding the degree of unavoidable leakage in stave pipe, concerning which inquiry is made, the author, in the summer of 1898, experimented on a 4½-mile section of 14-in. stave pipe designated as No. 13 in Table No. 5. The pipe is subject to a maximum pressure of about 60 ft., and an average of, perhaps, 25 or 30 ft., and is so located that the pressure is not much affected by the volume of discharge.

The rate of flow was measured by stationary weirs and hook-gauges set in masonry structures at each end of the line. The weirs are 4 ft. in length, and the rate of discharge was first reduced to a head of about 1 in. No loss was discernible. That the test might be made more delicate, and unavoidable errors better eliminated, a temporary weir only 8 ins. in length was substituted in both cases, and the flow further reduced to a head of about 1 in. Again, no loss was discernible, and the author considered himself justified in pronouncing the pipe without leakage. Each test was continued for some time after the low-stage uniform flow was attained.

Mr. O'Rourke thinks the limitations of economic usefulness of stave pipe, in reference to first cost, should be more closely defined. The author has already pointed out, page 57, that this line is not a constant, but is variable, not only for different points but even for the same point. Tables Nos. 8 and 9 are sufficiently extended to make manifest by inspection the position of this line at the points designated.

When buried in moist earth, no more serious objections than those the author has suggested can be urged against the use of thicker staves, except that it constitutes a needless increase in cost; but experience has amply demonstrated that when exposed to the action of the air, the process of wetting and drying incident to the varying rate of surface evaporation, will in a few years induce decay on the outer surfaces of thick staves.

On page 53 a long life for light-gauge riveted pipe, under favorable conditions of soil, is already conceded; but where soil destructive to steel pipe exists in such abundance as on the Pacific Coast, a note book, not to be misleading, should contain both extremes, rather than one.

There, also, will be found the author's reasons for including in the tables steel of greater thickness than the pressure alone requires.

If the statement therein made that "the exceptions are instructive, and fully vindicate the position assumed by many engineers, who, for permanent work, have recognized the necessity for a considerable thickness of metal, independent of the demand for a sufficient factor of safety against bursting, and who accord little favor to pipes of a very light gauge," is not sufficient, the author would suggest a study

of the minimum thickness adopted in most of the leading structures of this type. The following come at once to mind: Mr. Adams.

East Jersey Water Company	$\frac{1}{4}$ in.
New Rochester Works	$\frac{1}{4}$ "
Portland, Ore., Conduit	0.203 "
Coolgardie	$\frac{1}{4}$ "

The statement that the waters of the Pacific Coast States "are nearly always hard," will come as a shock to the engineers familiar with that region of granite and basalt; and likewise startling is the statement that tuberculation does not there exist. The writer has taken up cast-iron pipe in Oregon, which, after carrying water from a mountain stream—the source in the Northwest most frequently utilized—for nine years, was all so heavily tuberculated as to certainly reduce its carrying capacity 25%, while a recently completed and exhaustive examination of the works of the Los Angeles City Water Company by a commission of four engineers, of which the author was one, disclosed the fact that all pipes were tuberculated after being in service only six years. It was estimated by the commission that, on an average, the capacity of cast-iron pipe was diminished from this cause 10% in the first ten years, and thereafter at the rate of $\frac{1}{2}$ % per annum. Some of the pipes examined had been in service thirty years, and the water conveyed by them, containing about 26 grains of solid matter per gallon, chiefly carbonates of lime and magnesia, would be classed among the harder waters of the Pacific Coast.

The table of probable relative discharging capacities is not intended to be either prophetic or more exact than the present state of investigation warrants. Many modifications will doubtless be rendered necessary by the results of future experiment. The author has nowhere claimed more for the table than that it is abreast of the present knowledge, and while freely admitting the presence of apparent irregularities, and the need for much additional investigation, he has no hesitancy in affirming that the order of relative discharging efficiency of the different classes of pipes, as set forth in the paper, will not be changed. The difference will be one simply of degree, not of fact. That it is substantially abreast of present knowledge he strenuously insists; and, in addition to what has already been said relative to this matter, only wishes to refer the skeptical to that admirable review of nearly all existing data on the discharge of riveted pipes of large size, as set forth in Herschel's "115 Experiments" new and old, and to state that experiments on any conduit having a smooth interior, sheds much side light on the probable discharge of stave pipe. The admirable experiments of Messrs. Stearns and Fitz-Gerald,* on a double line of 4-ft. cast-iron pipe, tuberculated and

* *Transactions*, Am. Soc. C. E., Vol. xxxv, p. 241.

Mr. Adams. clean, are valuable in this connection.

Mr. Holbrook says stave pipe was in use as early as 1865. Mr. J. D. Fouquet,* M. Am. Soc. C. E., says as early as 1850. J. T. Fanning,† M. Am. Soc. C. E., says he built a line 6 ft. in diameter at Manchester, N. H., in 1874. Mr. Le Conte says it has been in use eight years.

All that Mr. Patton states regarding the experience with stave pipe at Cheyenne is exactly what might be expected under conditions so manifestly unsuited for its use as there prevailed.

The author has from time to time heard that growths may occur in stave pipe, but has yet to learn of a single instance where anything of the kind has occurred, with the pipe constantly full and under pressure.

* *Transactions*, Am. Soc. C. E., Vol. xxxi, p. 172.

† *Transactions*, Am. Soc. C. E., Vol. vi, p. 72.